More gallium

Meeting 22/11

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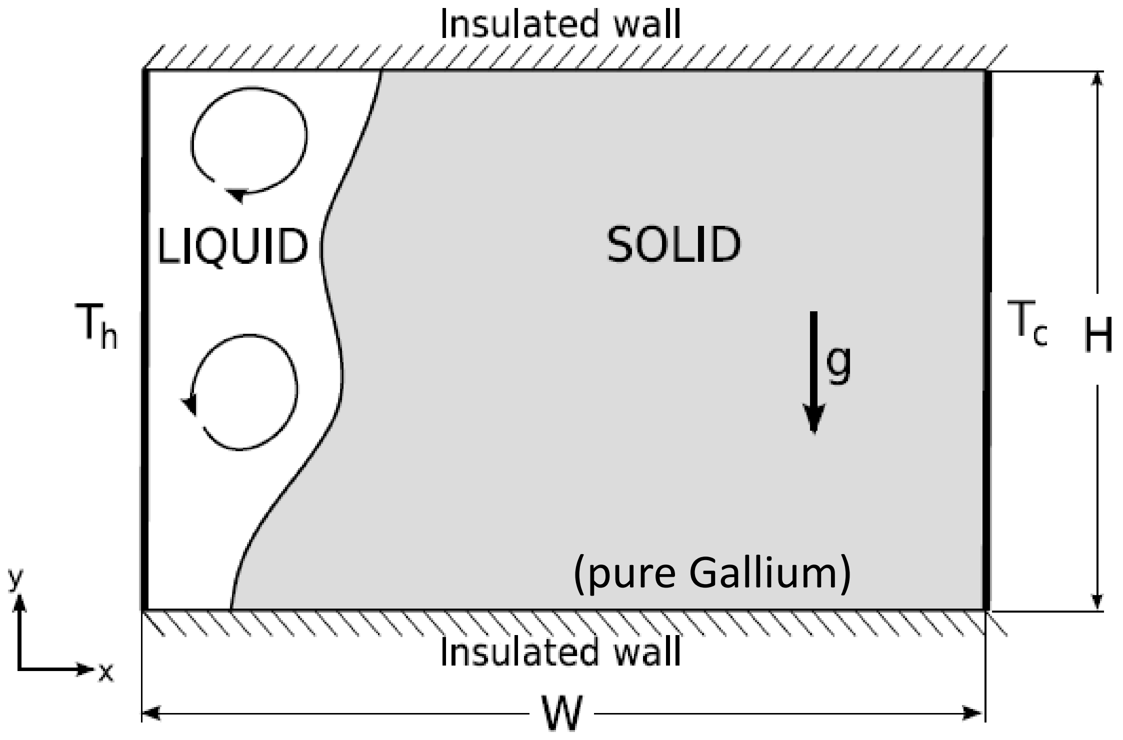
Content

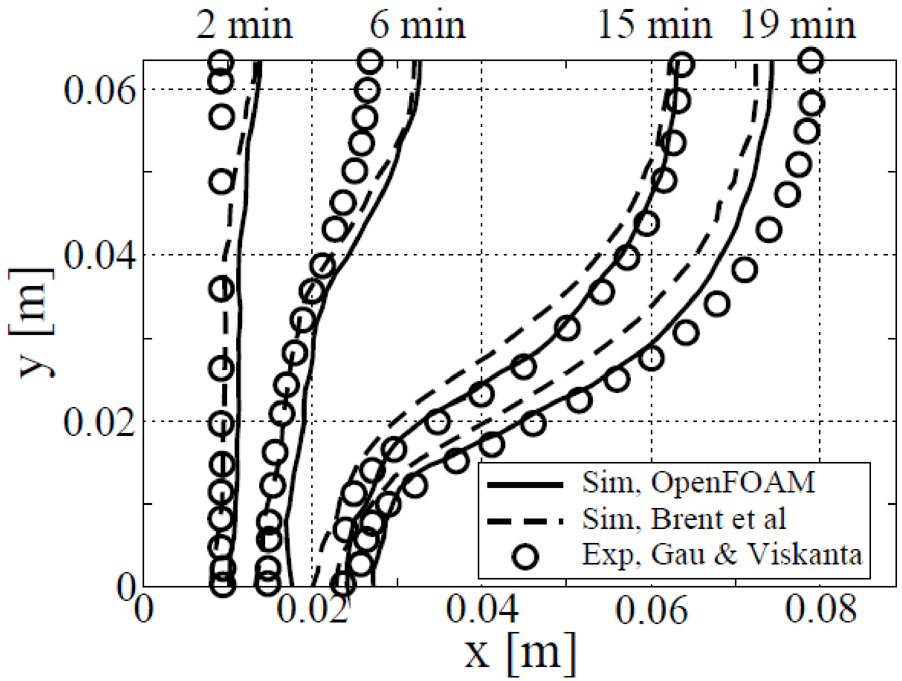
Gallium melting test case

- Reminder
- Parameter study
  - Mesh size
  - Boundary condition
  - Regularization
- Discussion
- Remaining issues
- Outlook

Reminder: Gallium melting test case

- Validate
  - Latent heat
  - Solid flow resistance
  - Buoyancy
- Compare front evolution
  - Sim. by Saldi (2012)
  - Sim. by Brent et al. (1988)
  - Exp. by Gau & Viskanta (1986)





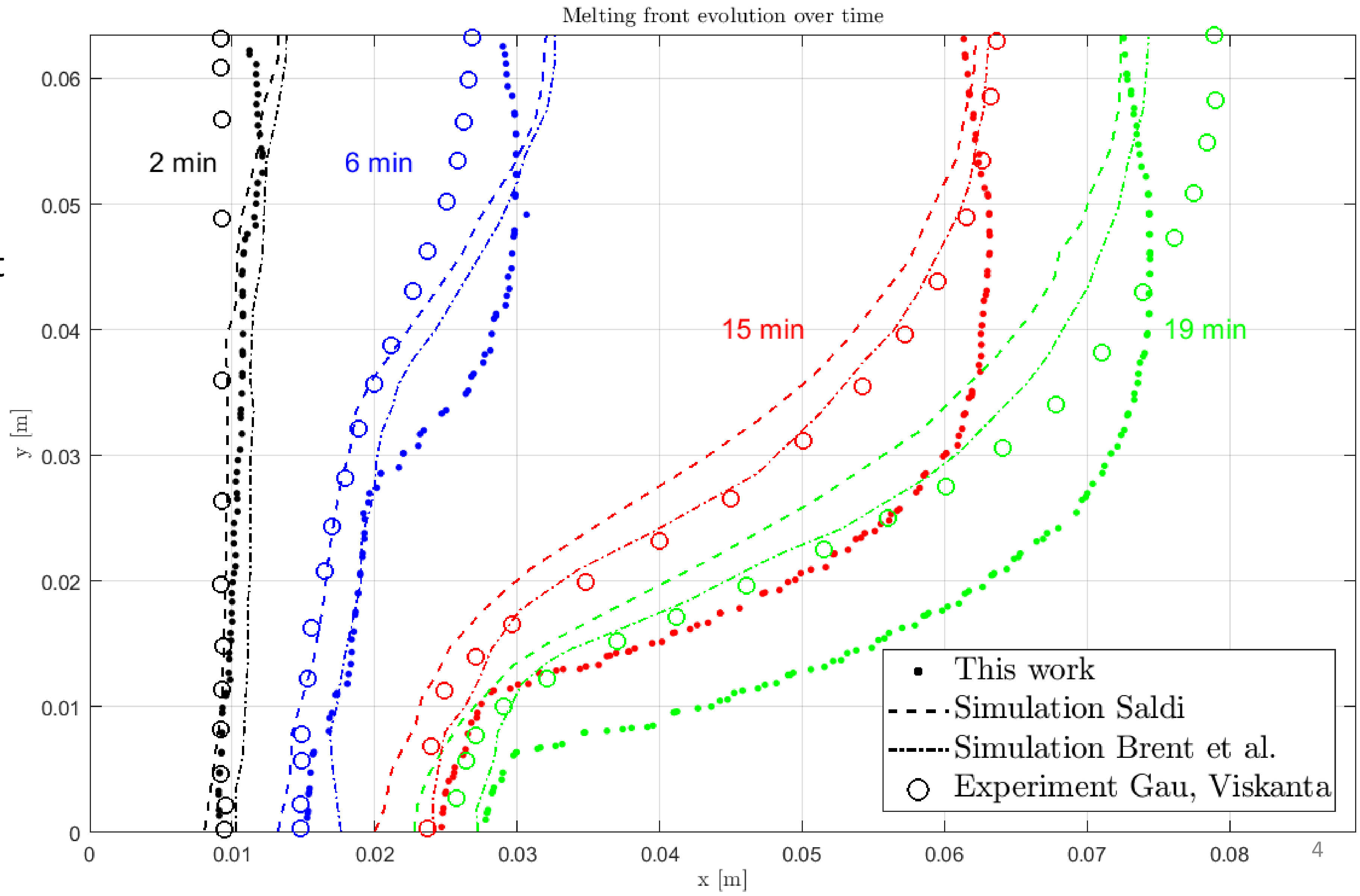
Reminder: Results do not match literature well

Fine mesh

Small ΔT_{reg}

No-slip boundaries

- Conduction dominated part agree well with simulations
- Convection dominated parts do not agree
  - Shape
    - “Carved out” mid-section
    - Very convex
    - Sharp transition to conduction part
  - Advancement
    - Too short at 6 min
    - Too far at 15 min
    - Too short at 19 min



Parameter study

Reference test case

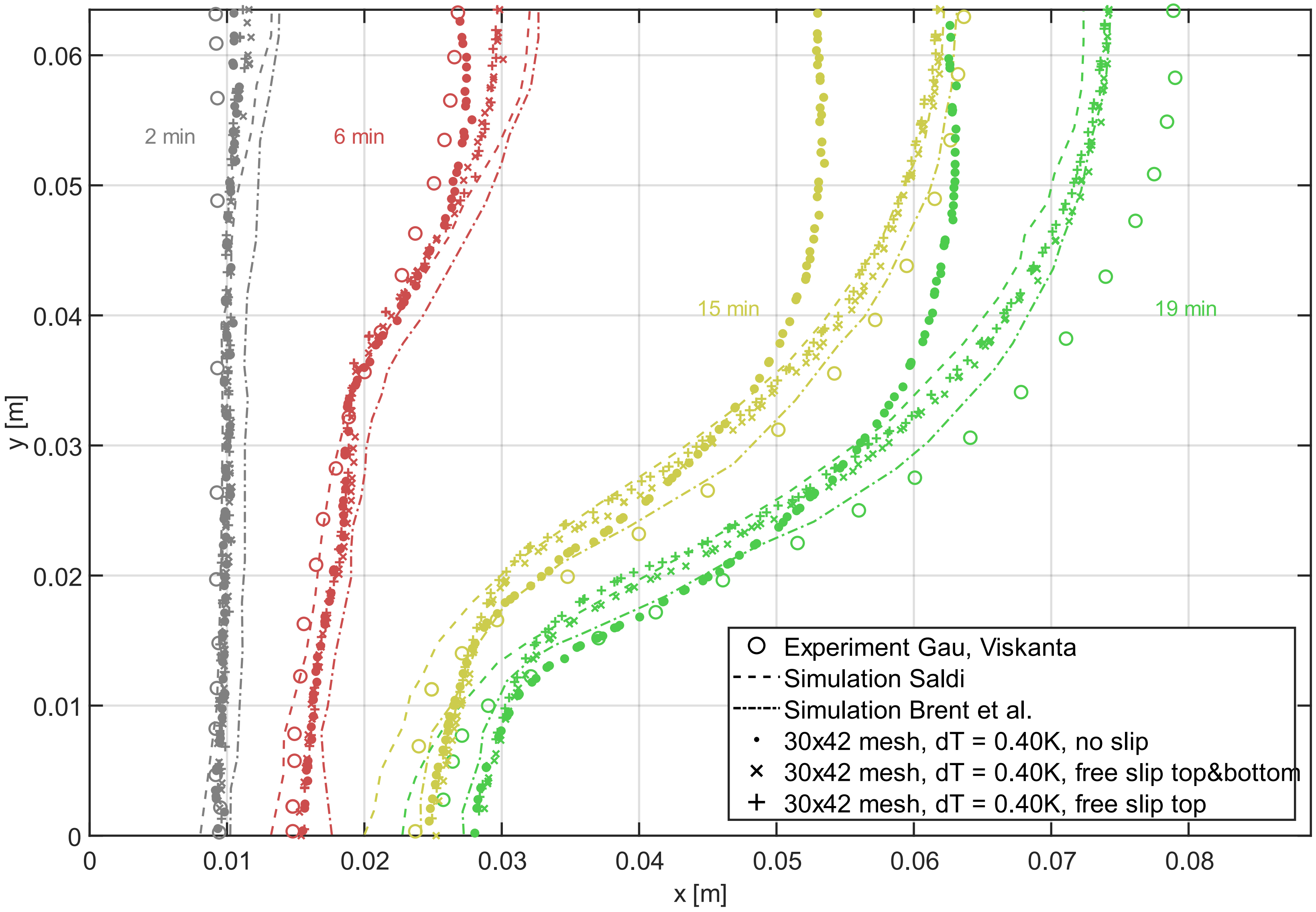
Important parameters	Hypothesis
Boundary condition	Free slip condition → shift up impinging hot fluid → correct shape of melting front
Mesh size	High mesh resolution → Complex flow phenomena captured → Altered melting front
Regularization	Sharp melting front → Higher T gradient → Increased heat flux → Faster front advancement
Neglected parameters	
Structured/unstructured mesh	Uniform element orientation towards melting front → may impact front advancement
(Possibly buggy) adaptive mesh refinement	Adding/removing nodes → violate energy conservation / affect front advancement
Time step / time integration	Many time steps (>20000) → tiny errors can accumulate significantly
Strong/weak coupling	1. Solve heat eqn., 2. solve NS-eqn., 3. update nodal positions → thermal equilibrium lost

Which boundary condition?

Free slip vs no slip

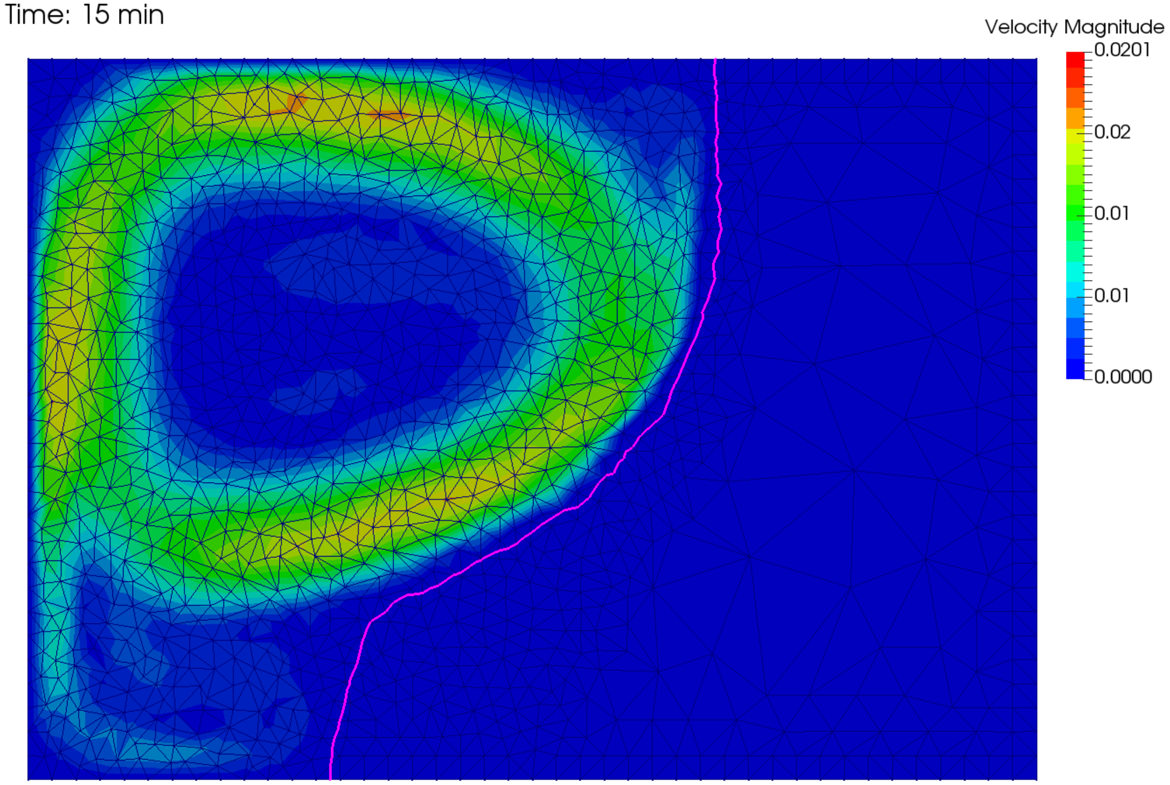
- Justification no slip:
  - Brent uses it
  - Saldi maybe uses it?
  - Experiment uses closed box
- Justification free slip:
  - Thin boundary layer?
    → Free slip everywhere
  - No contact with top wall due to shrinkage?
    → Free slip at top only

→ Free slip at bottom doesn't matter

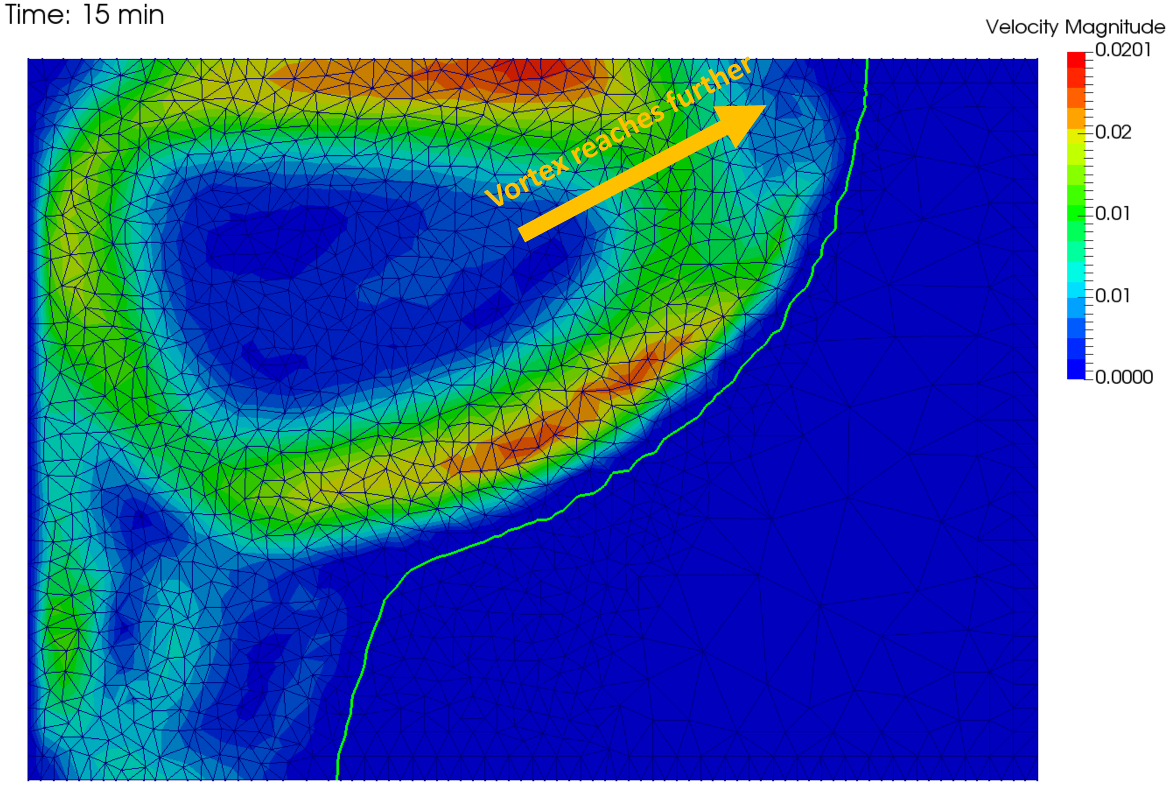


Boundary condition → melting front shape

No-slip all boundaries



Free slip top and bottom boundaries

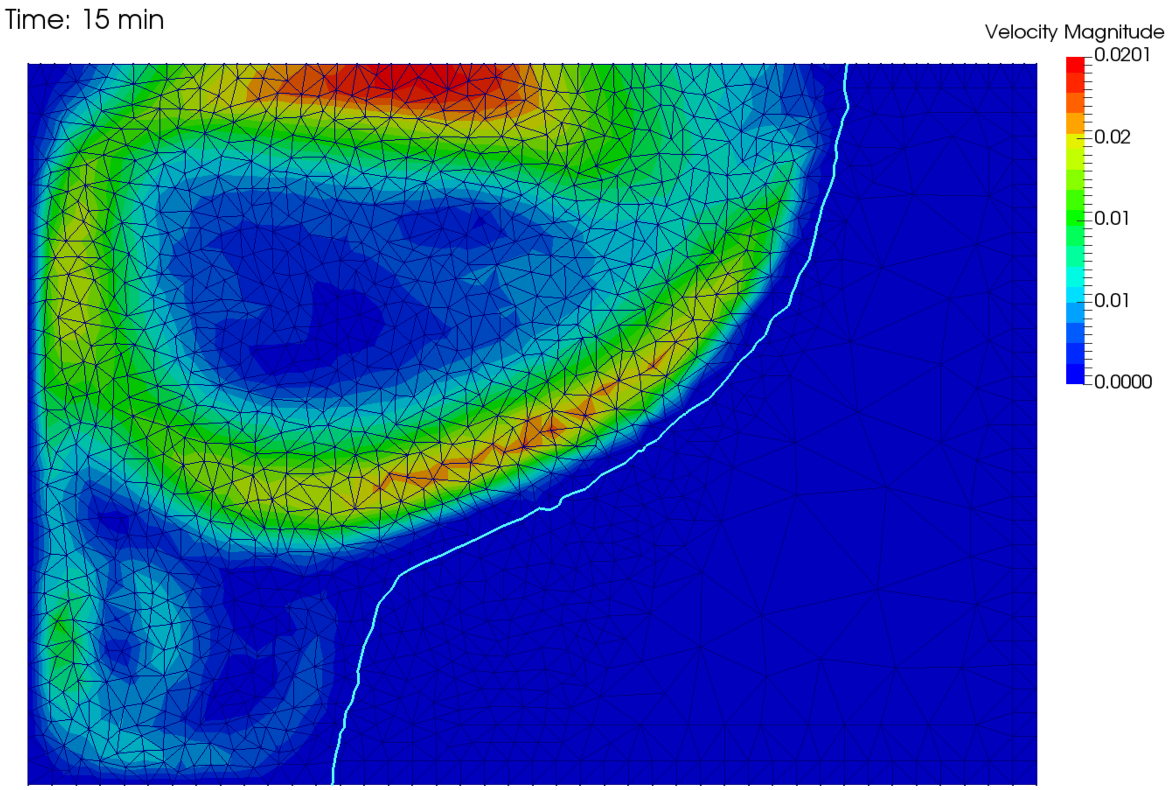


Regularization: $\Delta T_{reg} = 0.2\text{K}$

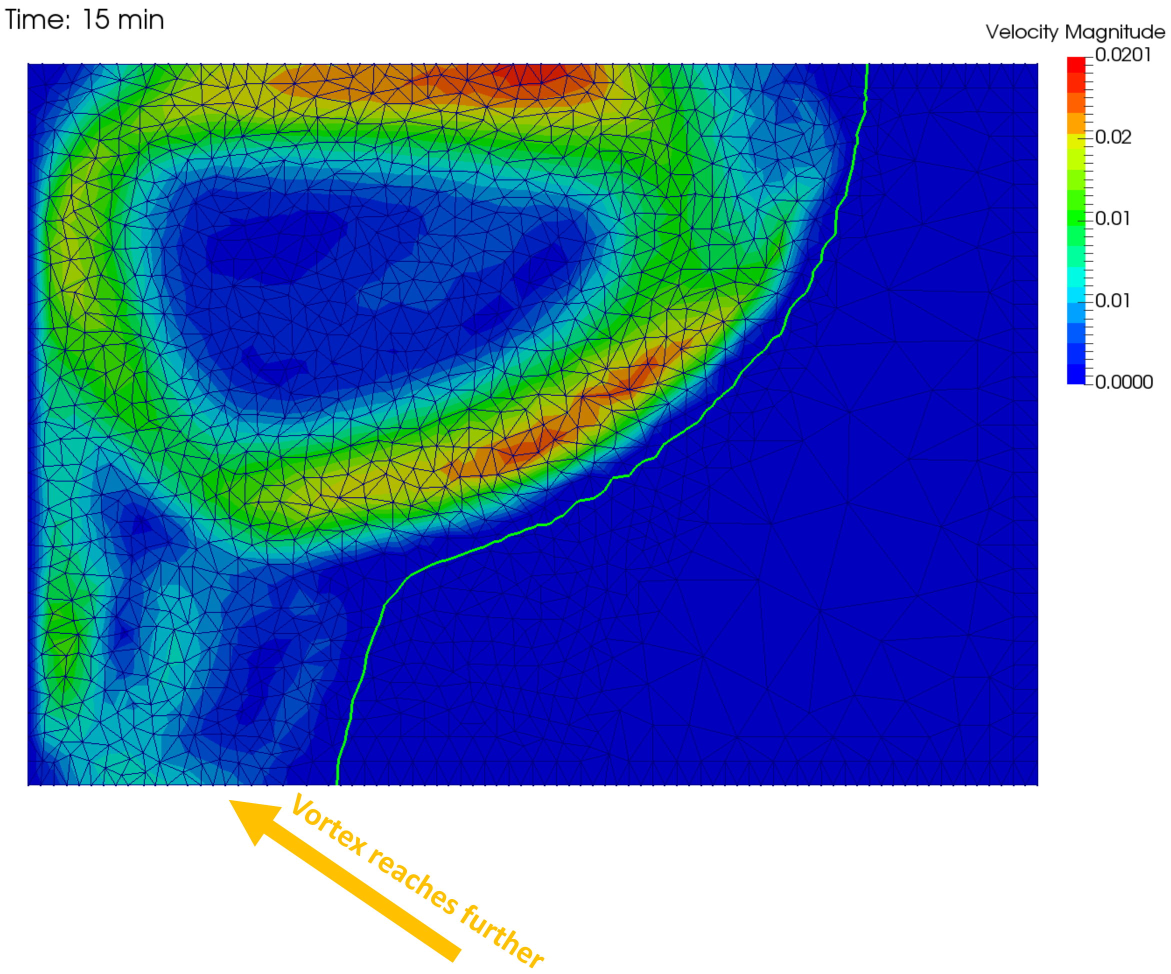
Mesh: 31x43 = 1260 nodes (coarse)

Boundary condition → melting front shape

Free slip top boundary



Free slip top and bottom boundaries



Regularization: $\Delta T_{reg} = 0.2\text{K}$

Mesh: 31x43 = 1260 nodes (coarse)

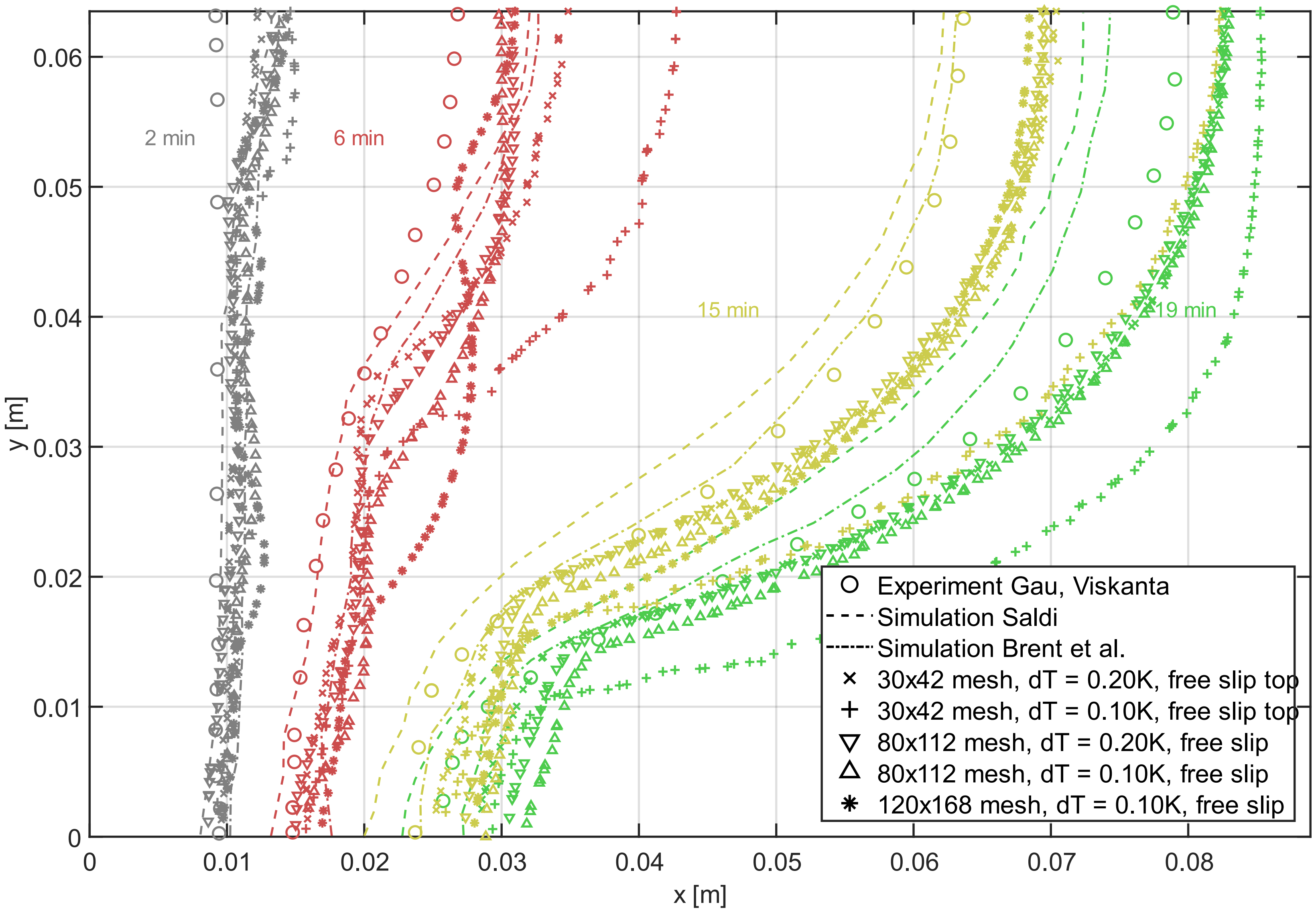
Which boundary condition?

Different meshes

Different phase transition

→Trends?

- Everything same at 2 min
- Great dispersion at 6 min
- Coarse mesh + thin transition region
  → front much too fast
- Other combinations agree with one another, but not with literature



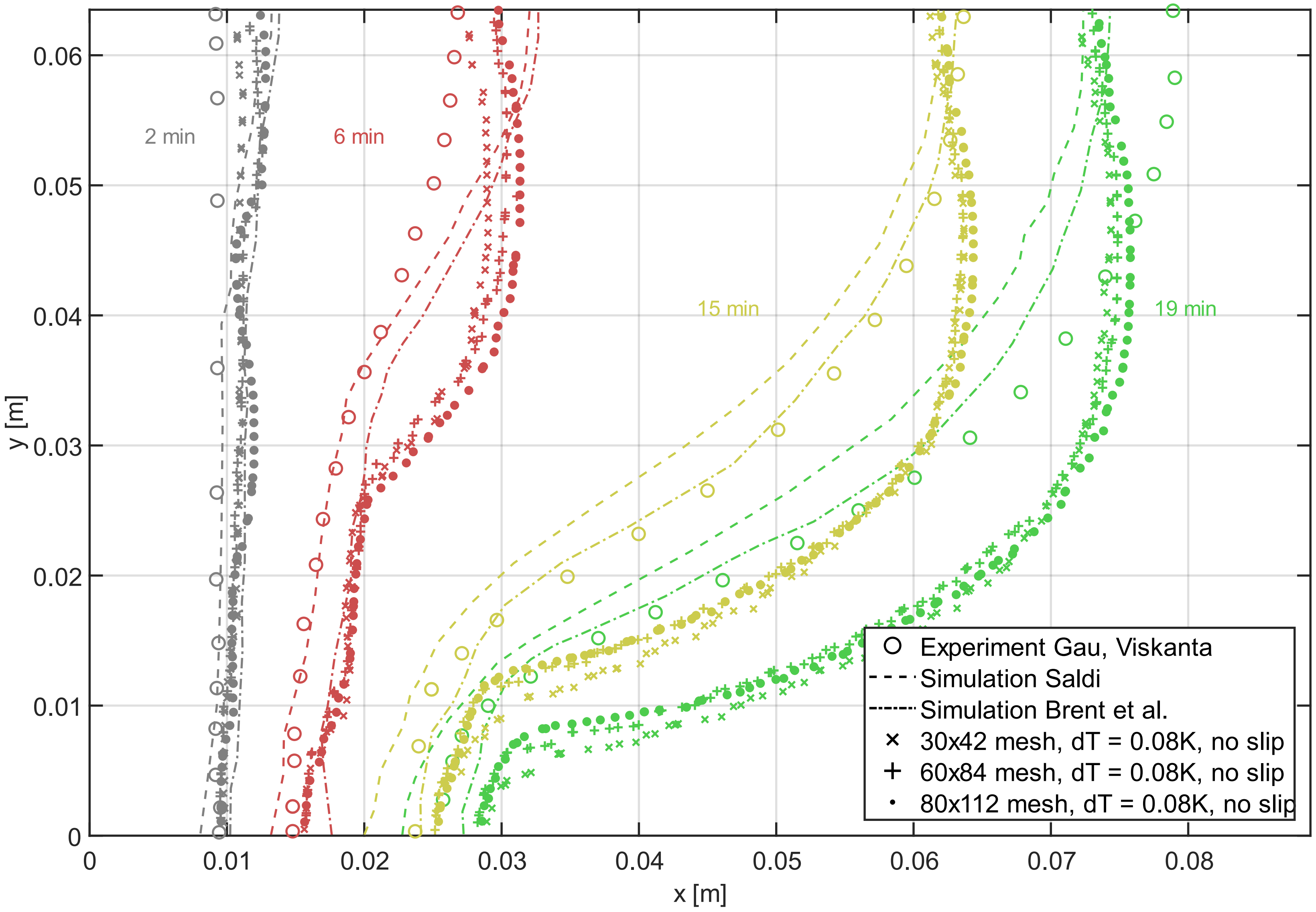
Mesh

All no slip

Thin transition

→Effect

- Little mesh dependence



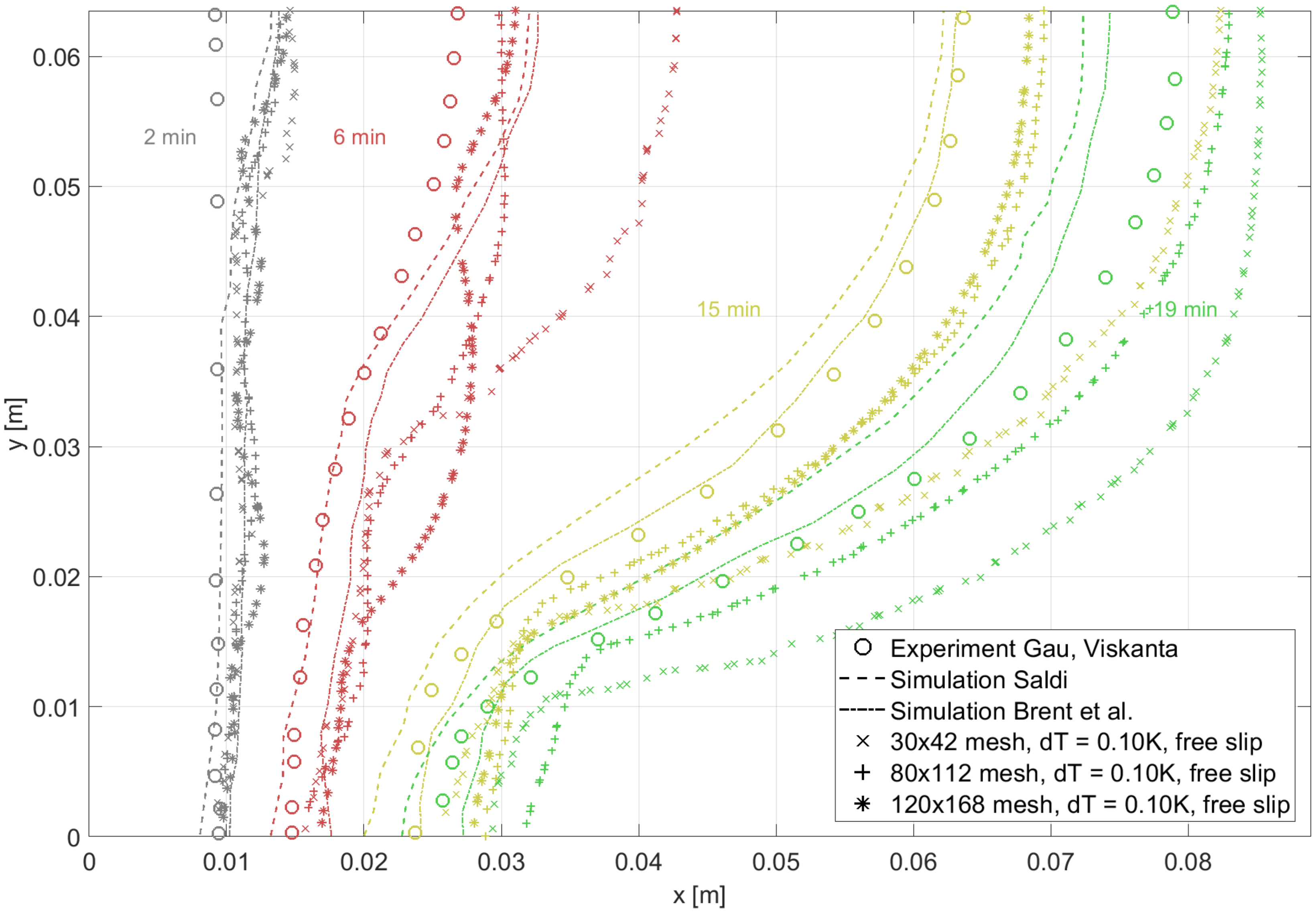
Mesh

All free slip

Thin transition

→Effect

- Strong mesh dependence when coarse
- Little mesh dependence when fine
- 6 min: significant variation of front shape



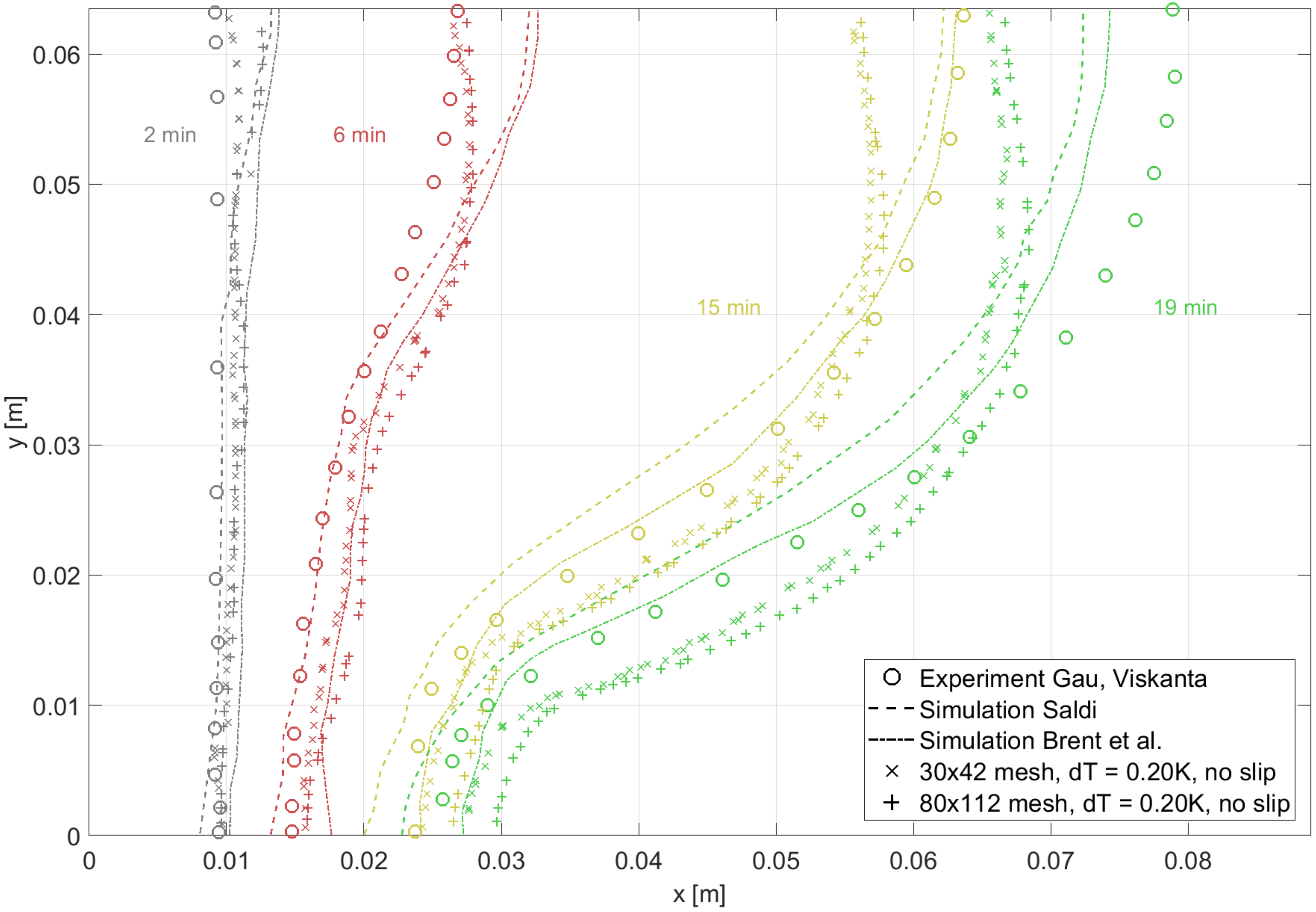
Mesh

All no slip

Thick transition

→Effect

- Little mesh dependence



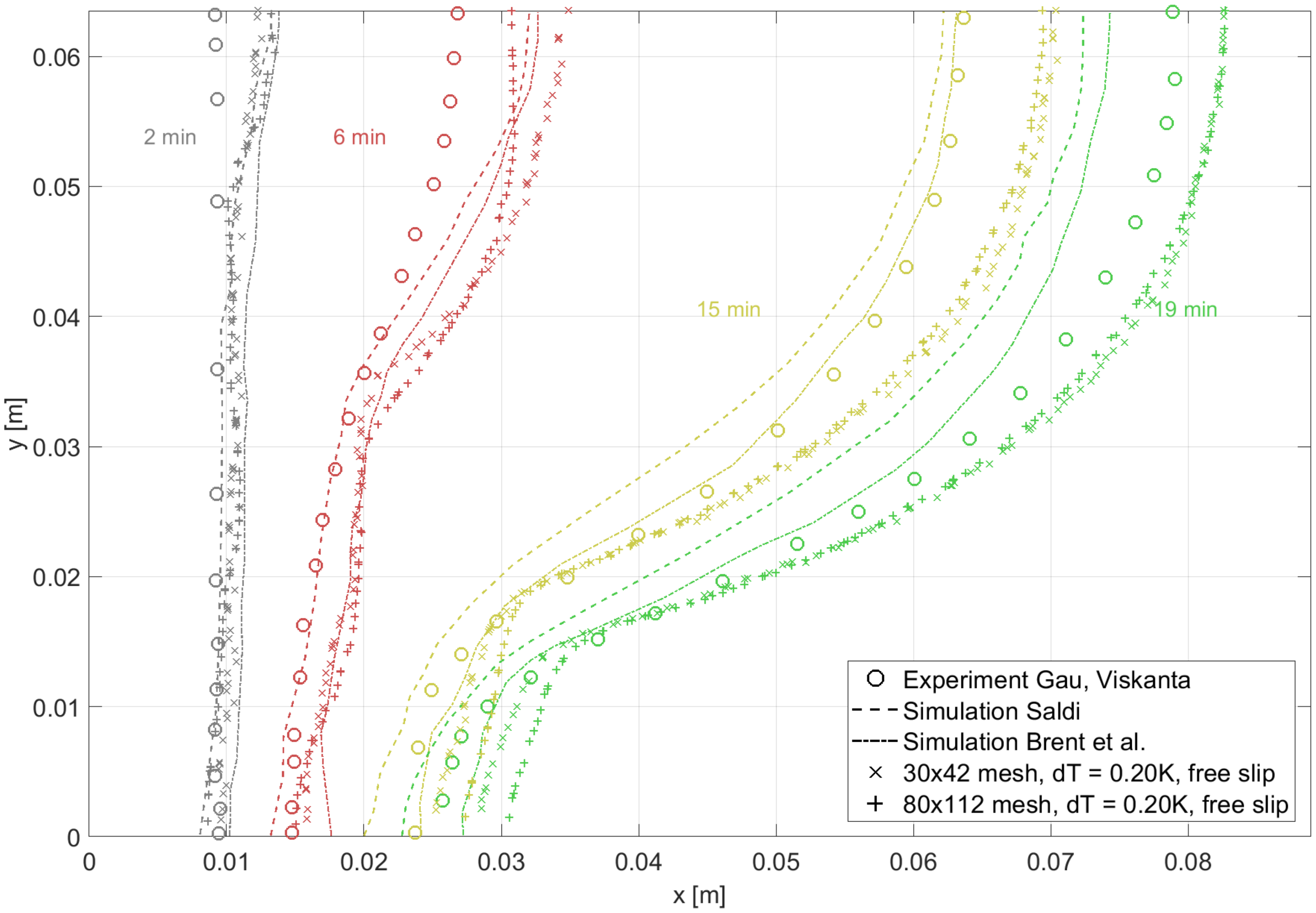
Mesh

All free slip

Thick transition

→Effect

- Little mesh dependence
- Good agreement at 2 min and 6 min



Regularization

All no slip

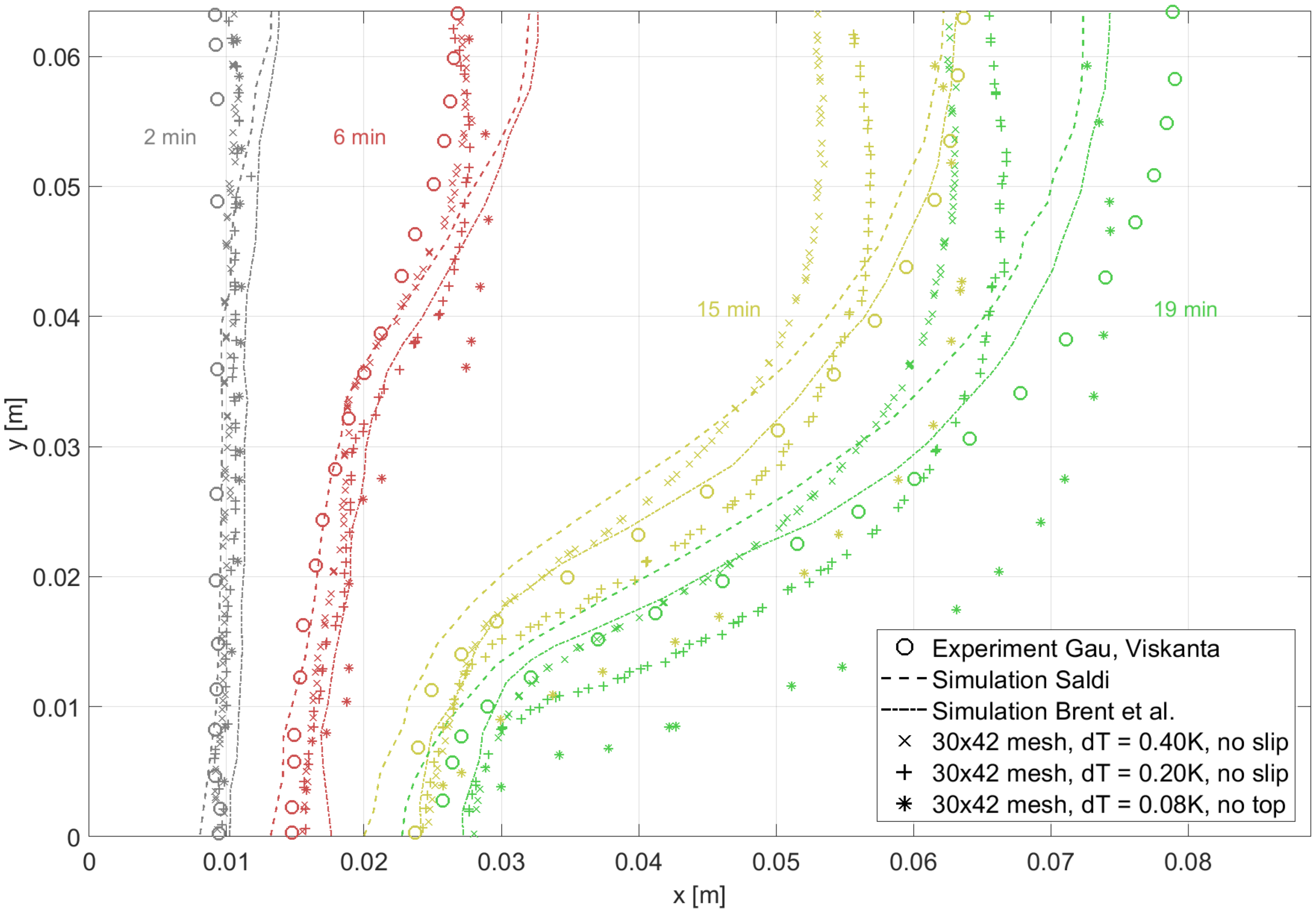
Coarse mesh

Thin: $\Delta T_{reg} \approx 0.1K$

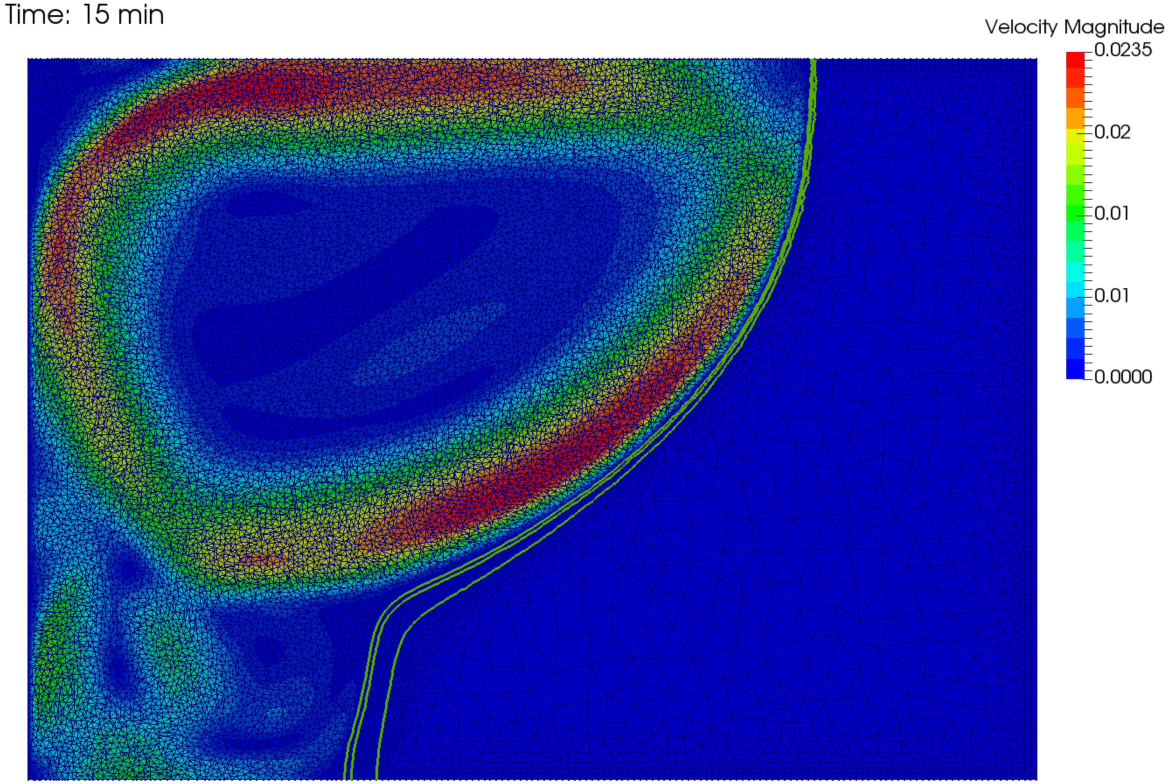
Thick: $\Delta T_{reg} \approx 0.4K$

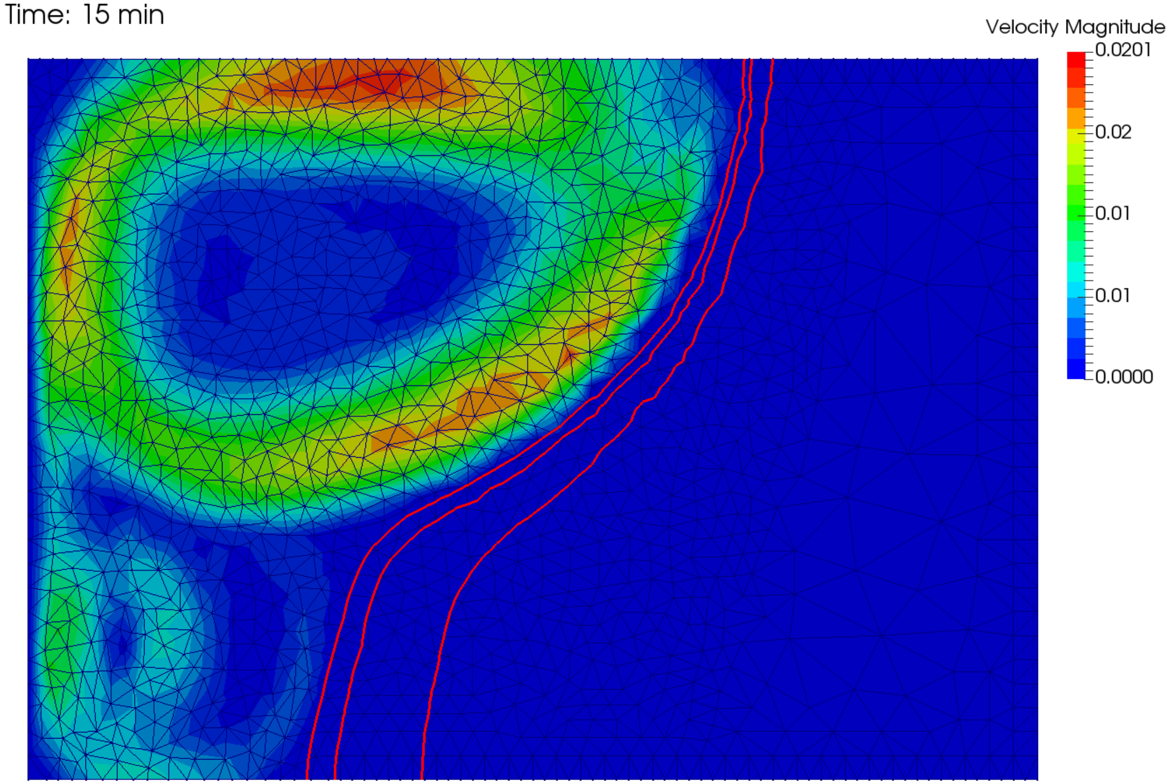
→Effect

- Very strong mesh dependence
- Thin → thick
  Left ← right



Regularization





Regularization: $\Delta T_{reg} = 0.1\text{K}$
Mesh: 120x168 = 20160 nodes (fine)

Regularization: $\Delta T_{reg} = 0.4\text{K}$
Mesh: 30x42 = 1260 nodes (coarse)

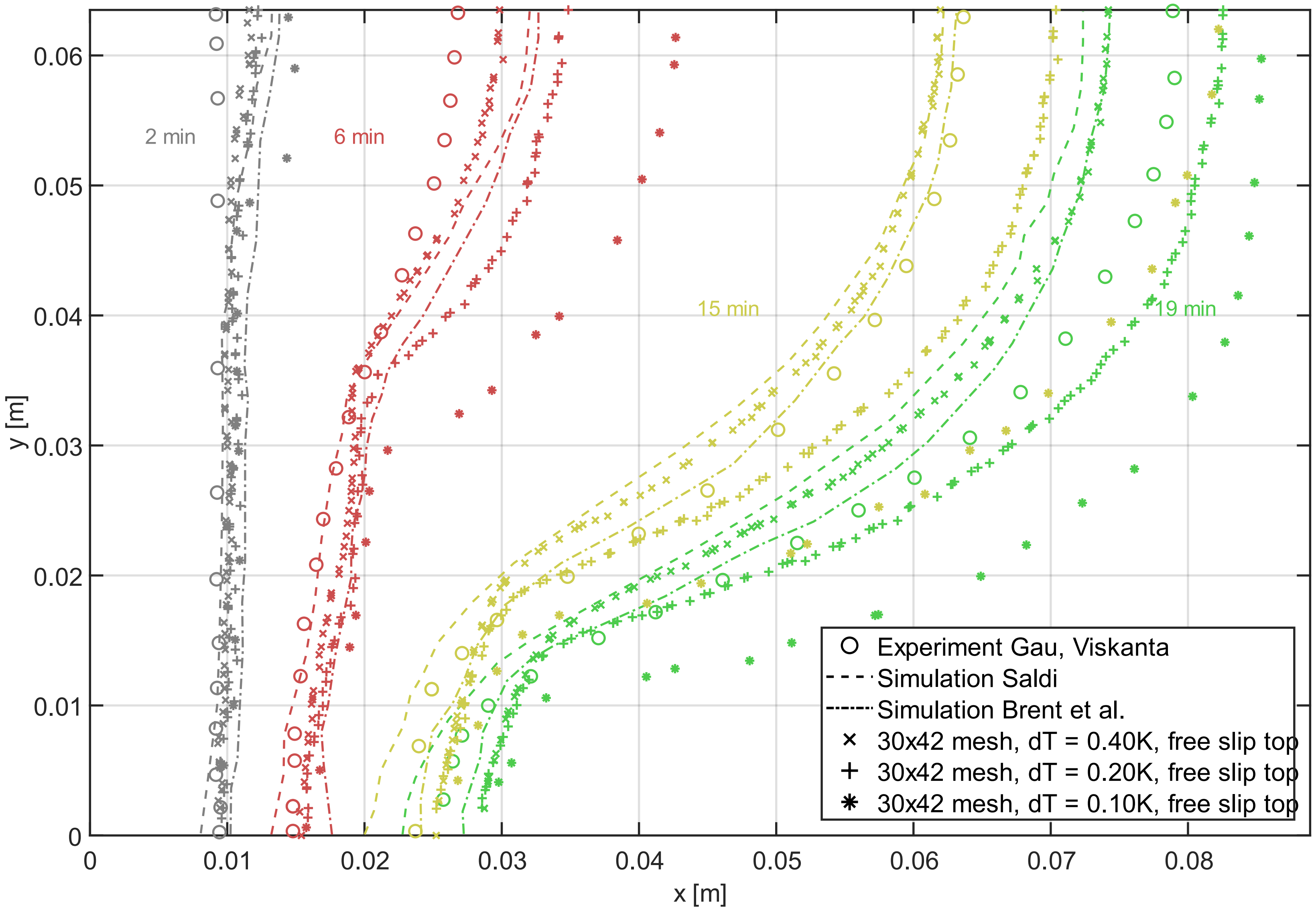
Regularization

All free slip

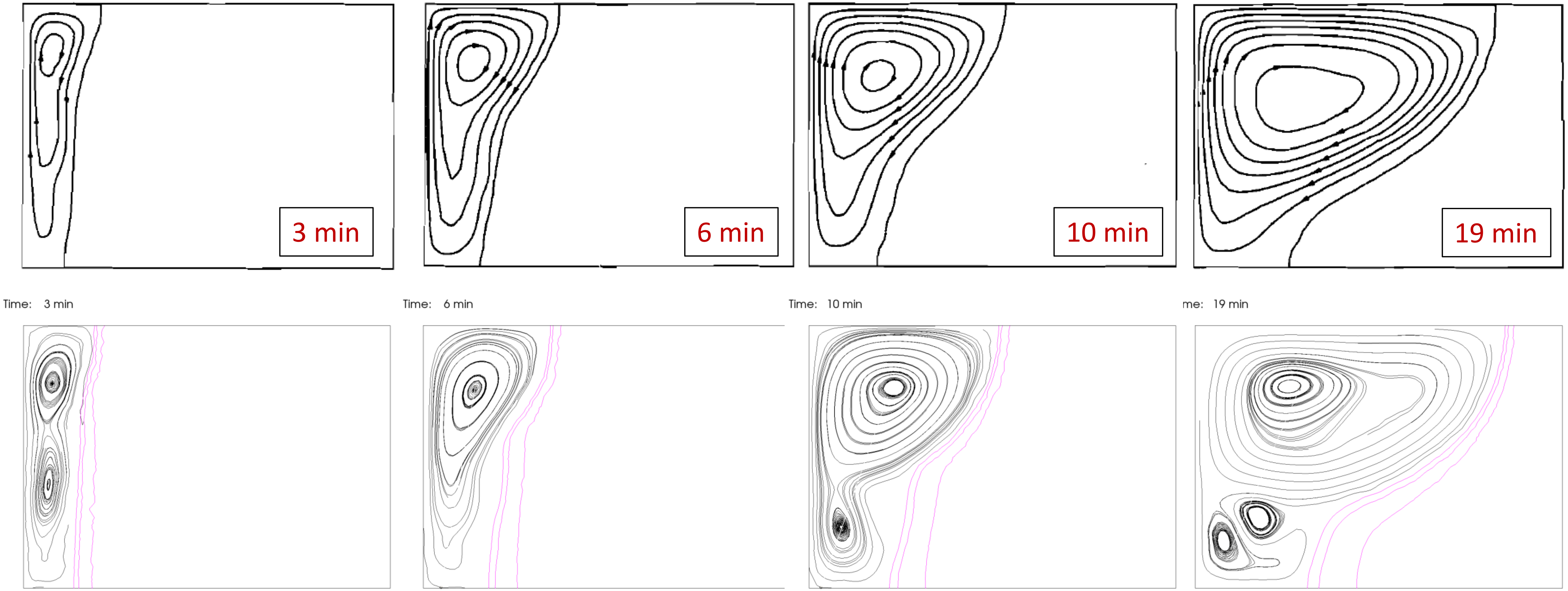
Coarse mesh

→Effect

- Very strong mesh dependence
- Thin → thick
  Left ← right
- Excellent agreement with literature simulations when
- $\Delta T_{reg} = 0.4\mathrm{K}$ on a coarse mesh might be best approximation of Brent's setup



Why does it match well?



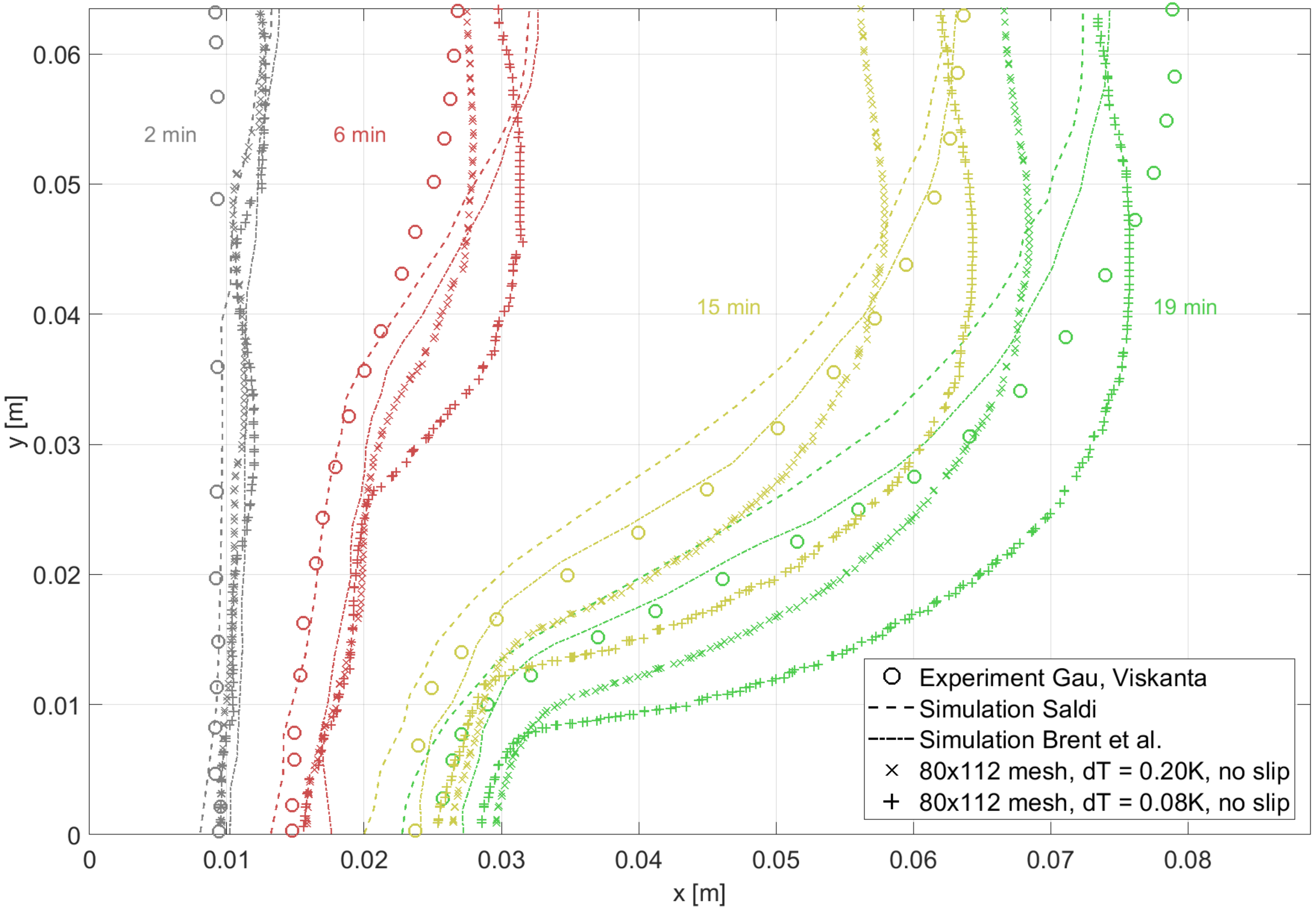
Which phase change interval width?

All no slip

Fine mesh

→Effect

- Very strong mesh dependence
- Thin → thick
  Left ← right
- Which one is best fit??



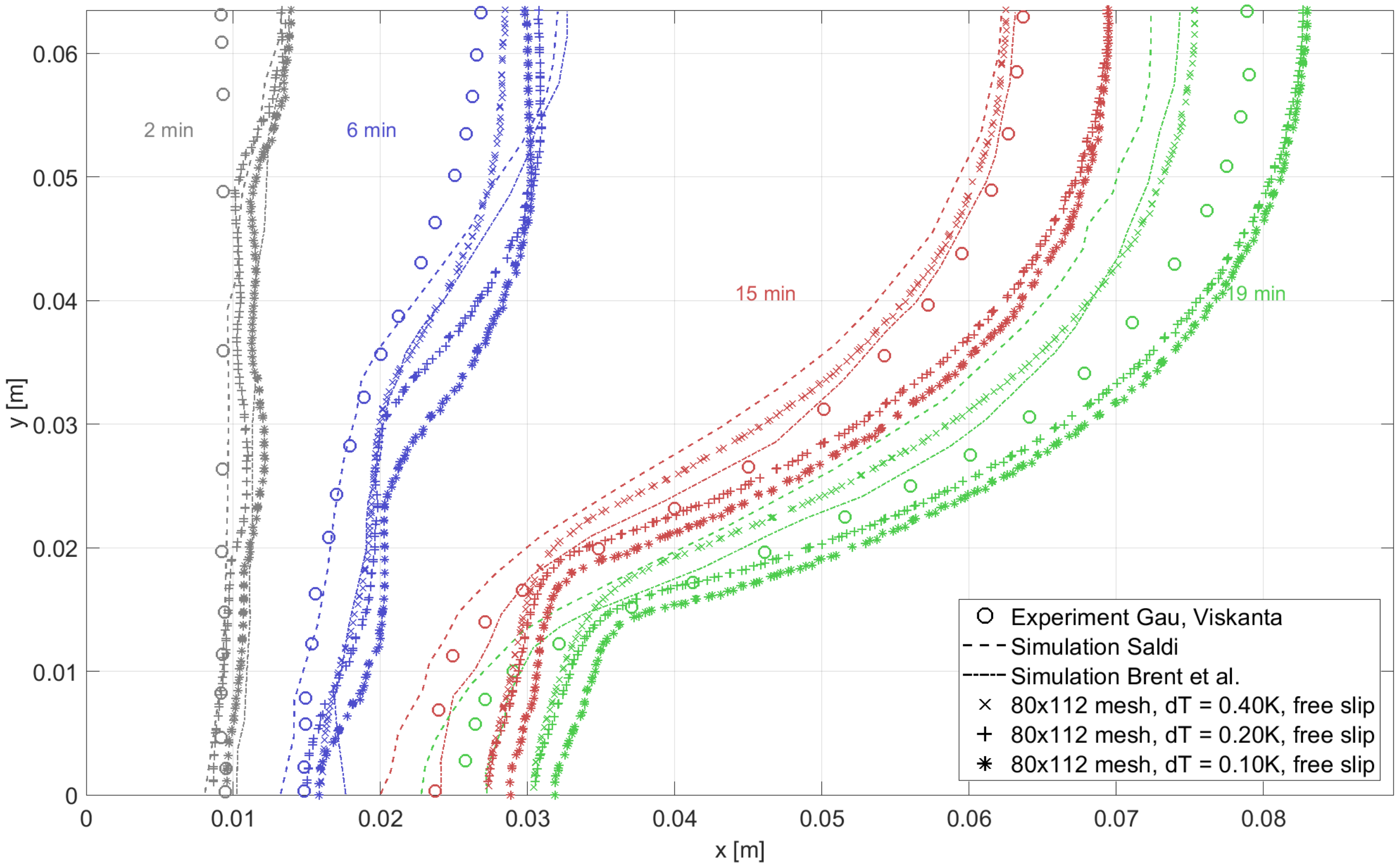
Which phase change interval width?

All free slip

Fine mesh

→Effect

- weak mesh dependence for low ΔT_{reg}
- Then surprising jump to the left from $\Delta T_{reg} = 0.2\text{K}$ to $\Delta T_{reg} = 0.4\text{K}$
- $\Delta T_{reg} = 0.4\text{K}$ on a fine mesh might be best approximation of Saldi's setup



Discussion

- Free slip at top → correct curve shape
- Free slip at bottom doesn't change much
- Fine mesh creates complicated vortex structure between 2 min and 4 min, very mesh sensitive, effects can be seen until 7min
- Using a coarse mesh and a large ΔT approximates well Brent's approach (and their results)
- Strong dependence on chosen ΔT for coarse meshes, less for fine meshes
- Weak mesh dependence, if free slip & ΔT is small, otherwise strong mesh dependence
- Very fine mesh might improve no-slip results?

Appendix

Literature 1: Gau & Viskanta (1988)

Method:

- Test cell filled with liquid Ga
- Fully solidified
- Turn on constant T side walls
- Let melt for a given time
- Melting interrupted, remaining liquid poured out quickly
- Melt front photographed or traced (?)

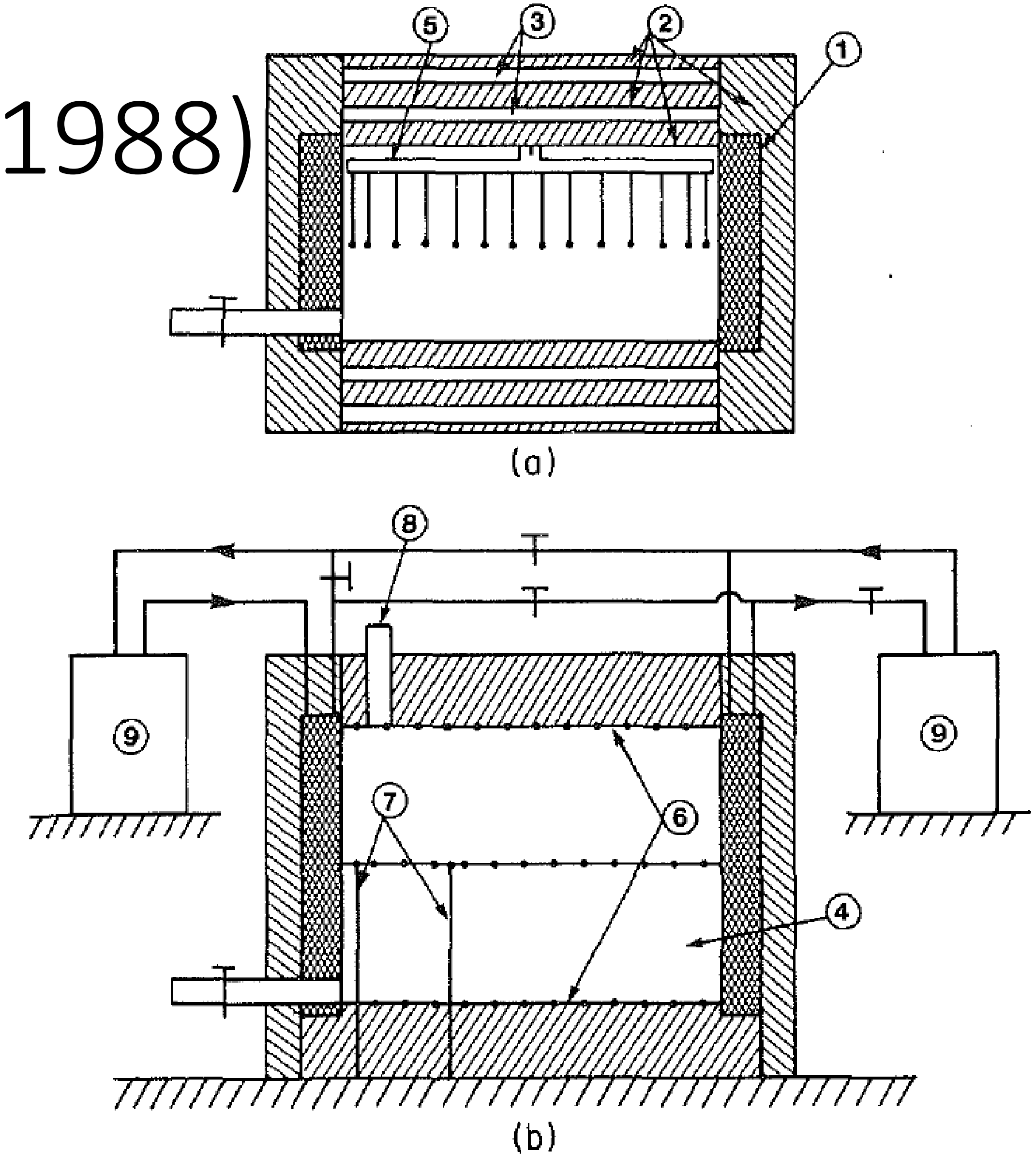


Fig. 1 Schematic diagram of the test cell, top view (*a*) and front view (*b*): (1) heat source and/or sink, (2) Plexiglass wall, (3) air gap, (4) phase-change material, (5) thermocouple rack, (6) thermocouples along the walls, (7) small-diameter thermocouples, (8) hole for filling material, and (9) constant temperature baths

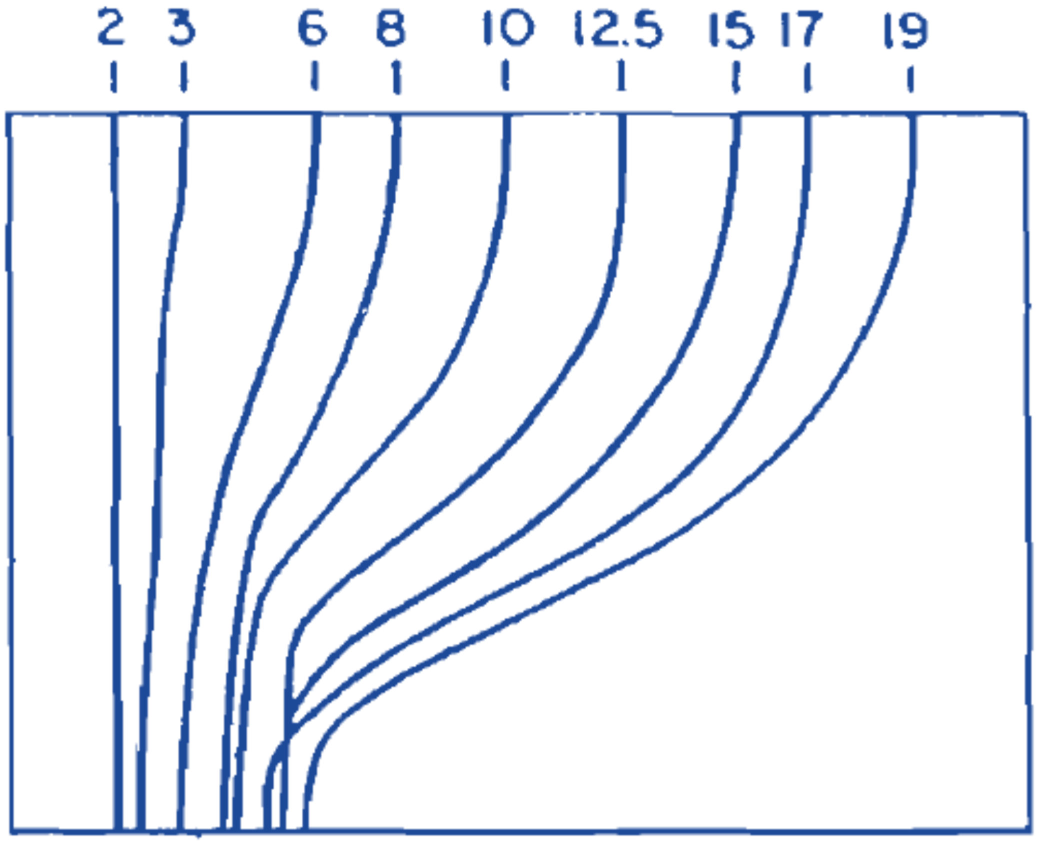
Literature 1: Gau & Viskanta (19886

Method: Test cell filled with liquid Ga, then fully solidified before turning on constant T side walls. After given time, melting interrupted, remaining liquid poured out quickly, melt front photographed or traced

+ Methods clearly described
+ Material properties clearly listed
+ Compares front position for all 9 times
+ Thermocouples might show unstable flow behavior

- Wetted top wall ensured after shrinkage? (--> feeder & riser?)
- 3D effects appear significant
- Effect of significant anisotropy of solid Ga not discussed

Literature 2: Brent et al. (1988)



Gau & Viskanta 1986 (exp.)

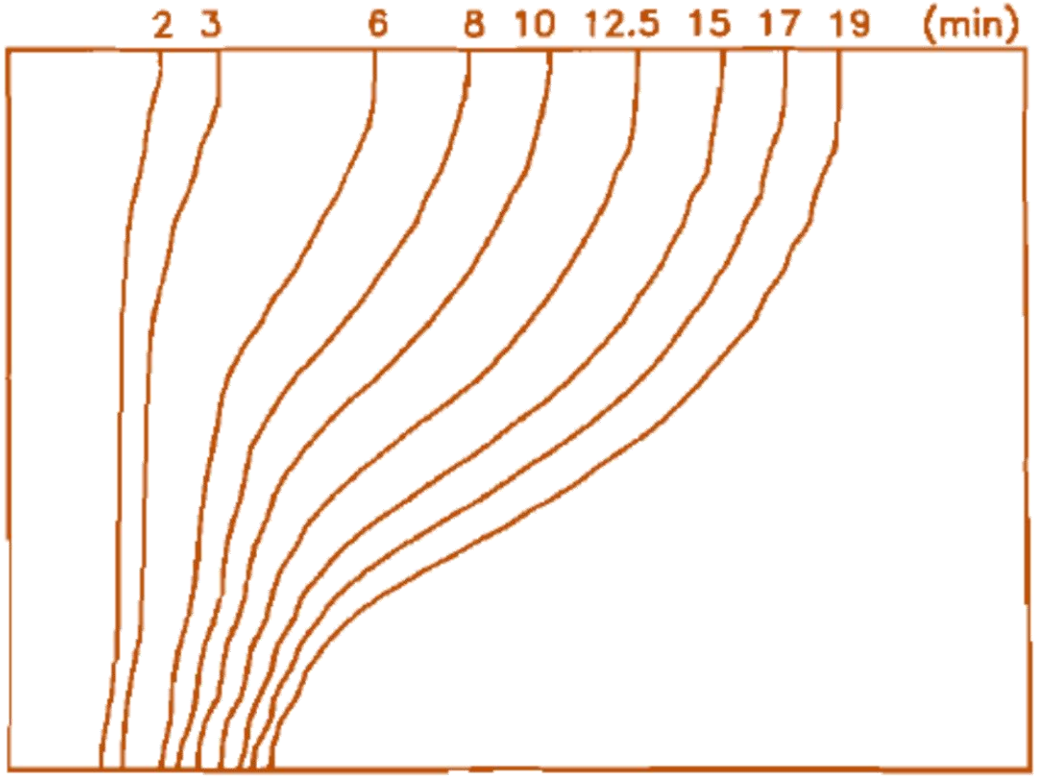
Literature 2: Brent et al. (1988)

Method: FVM + Darcy term + iterative nodal enthalpy scheme (Voller et al. 1991)

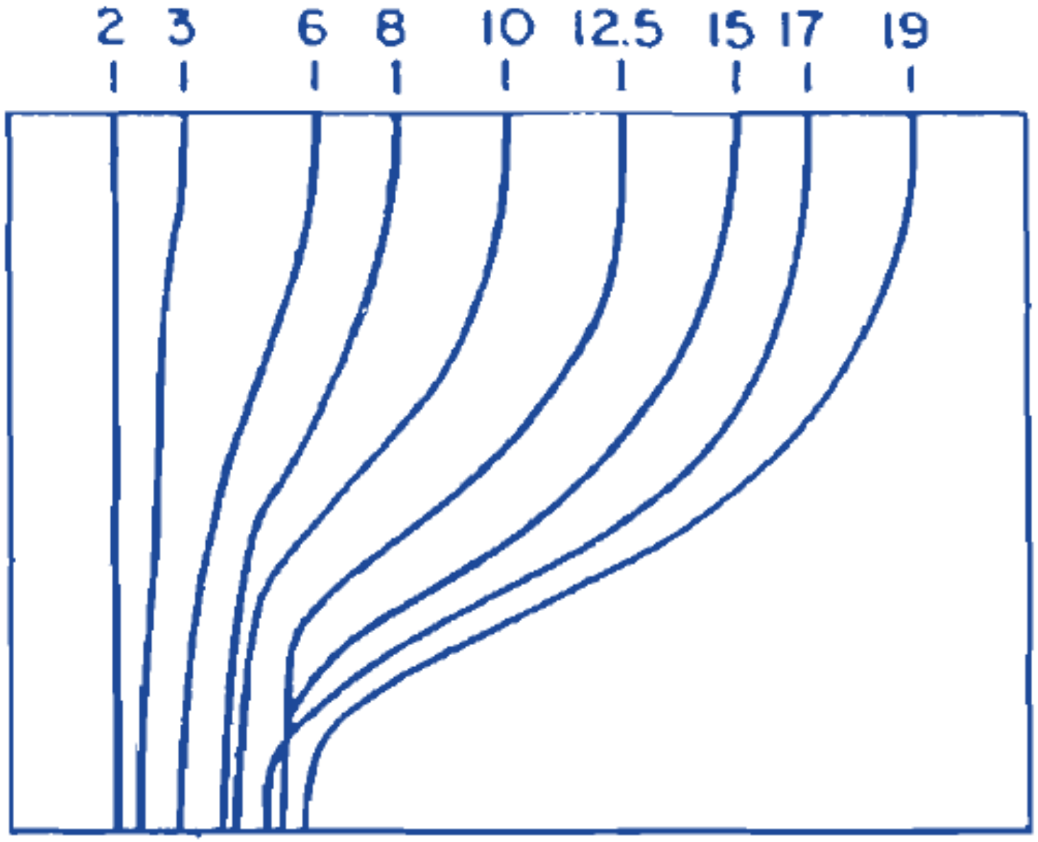
+ Also compares directly to Gau & Viskanta, 1986
+ Methods clearly described*
+ Material properties clearly listed
+ Compares front position for all 9 times
+ Streamlines and T isolines for 4 times (3, 6, 10, 19)

- Discussion of discrepancies very short
- No discussion of mesh size and mesh sensitivity (although the physics have strong multiscale character)
- *not clear which function for f_l is used
- Phase front graph based on nodal latent heat ($L/2$), not temperature -> how does it affect the result?

Literature 2: Brent et al. (1988)



Brent et al. 1988



Gau & Viskanta 1986 (exp.)

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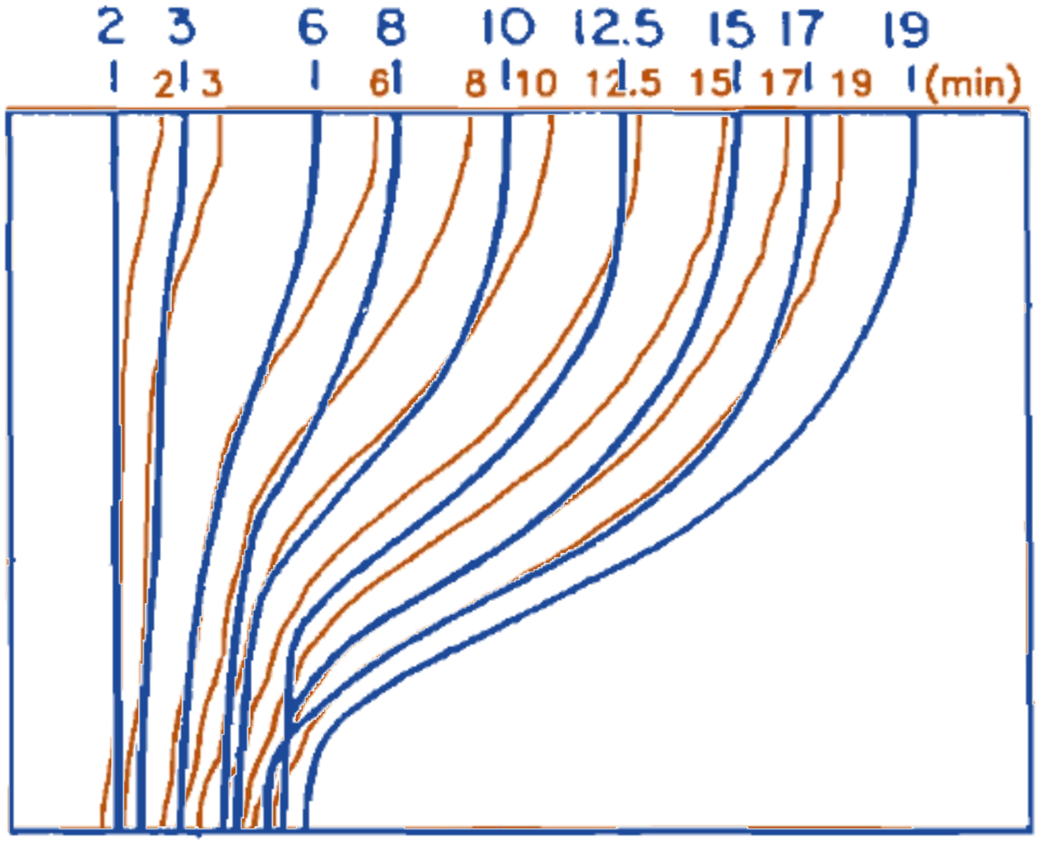

Brent et al. 1988

Gau & Viskanta 1986 (exp.)

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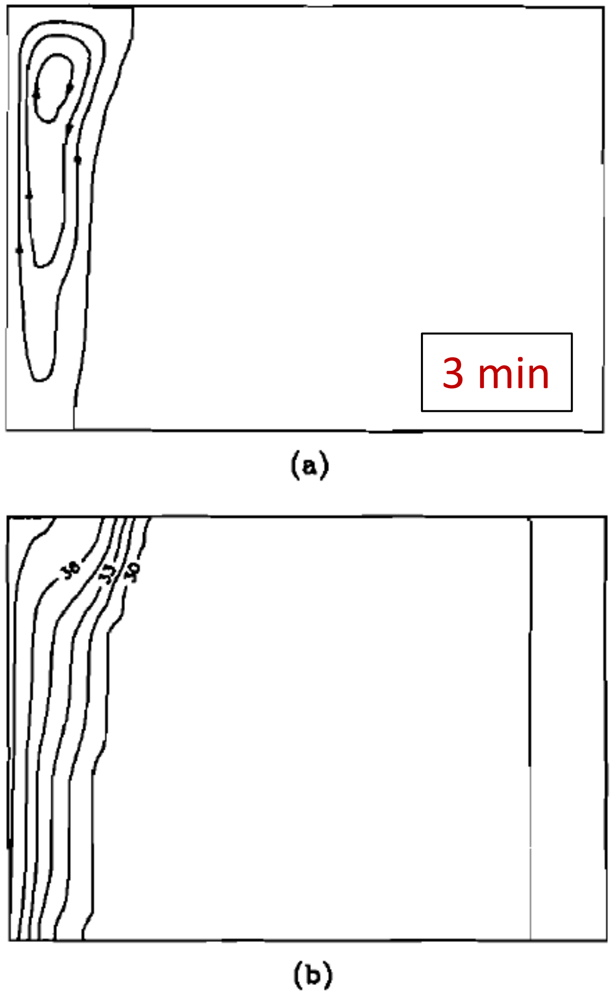


Fig. 3 Flow and temperature fields at 3 min for the two-dimensional melting of gallium. Panel (a) depicts the streamlines and melt front; panel (b) the isotherms.

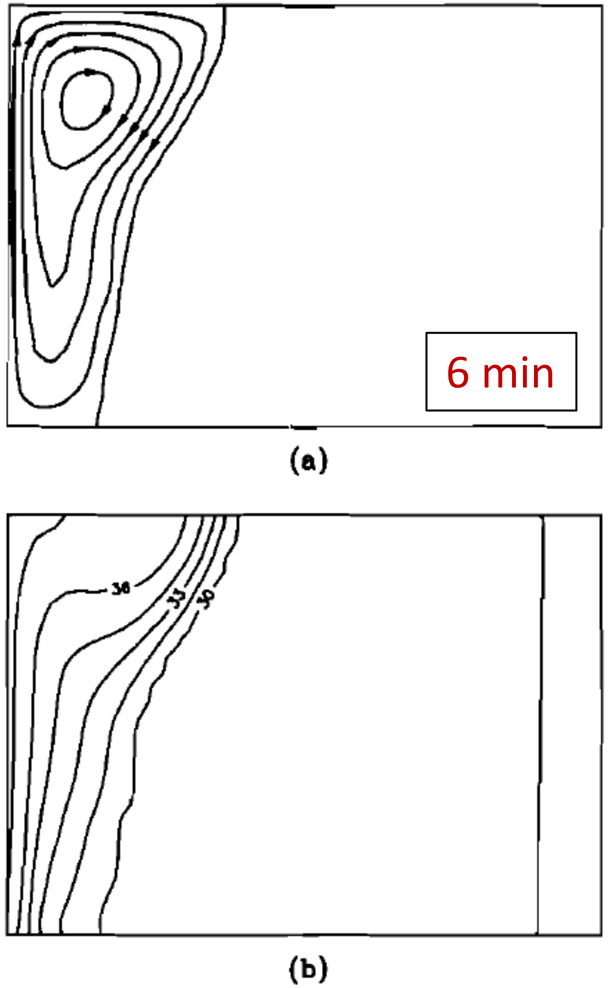


Fig. 4 Flow and temperature fields at 6 min for the two-dimensional melting of gallium. Panel (a) depicts the streamlines and melt front; panel (b) the isotherms.

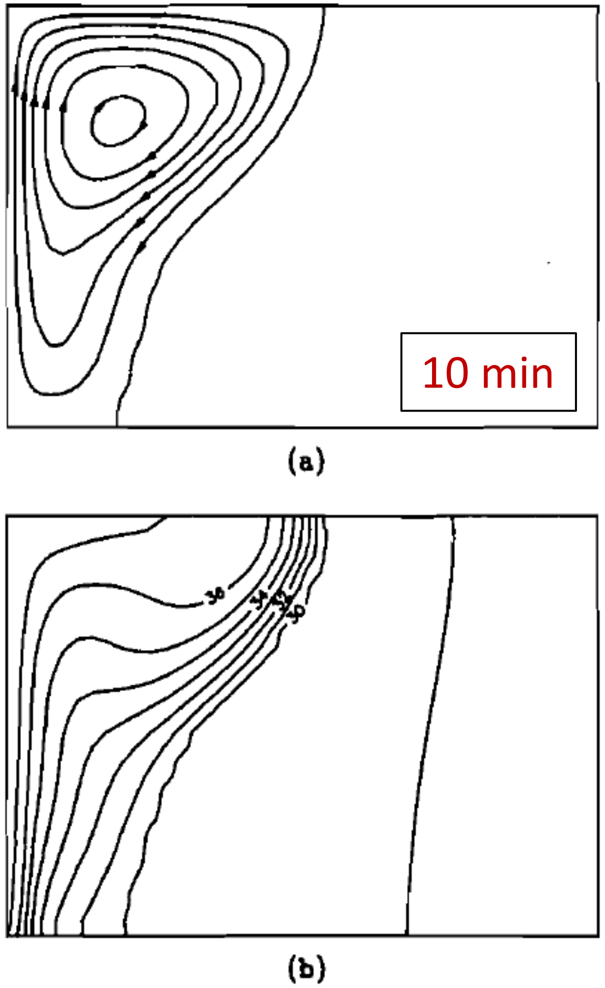


Fig. 5 Flow and temperature fields at 10 min for the two-dimensional melting of gallium. Panel (a) depicts the streamlines and melt front; panel (b) the isotherms.

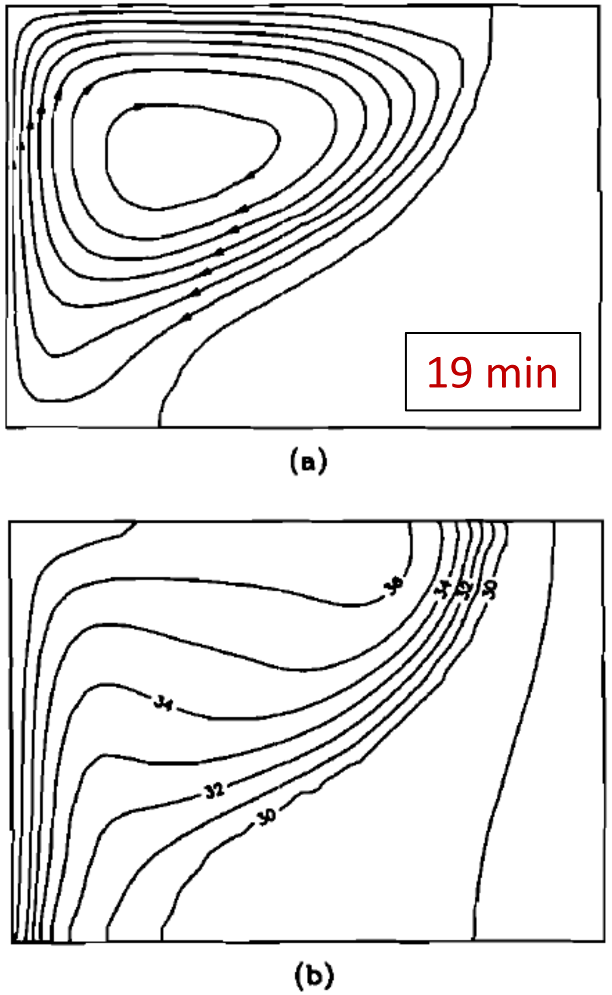


Fig. 6 Flow and temperature fields at 19 min for the two-dimensional melting of gallium. Panel (a) depicts the streamlines and melt front; panel (b) the isotherms.

Literature 3: Saldi's PhD thesis (2012)

Method: FVM + Darcy term + iterative nodal enthalpy scheme (Voller et al. 1991)

+ Compares and reviews briefly other publications
+ Methods clearly described
+ Material properties clearly listed
+ Small mesh study regarding early flow field (multiple vortices) with velocity vector plots

- Numerical settings (e.g. time step, mesh size, convergence criteria etc.) not given/not clear
- Phase front comparison only done for 4 times (2, 6, 15, 19 minutes)
- Velocity vector plots only for 2 min and no magnitude given and no discussion

Literature 3: Saldi's PhD thesis (2012)

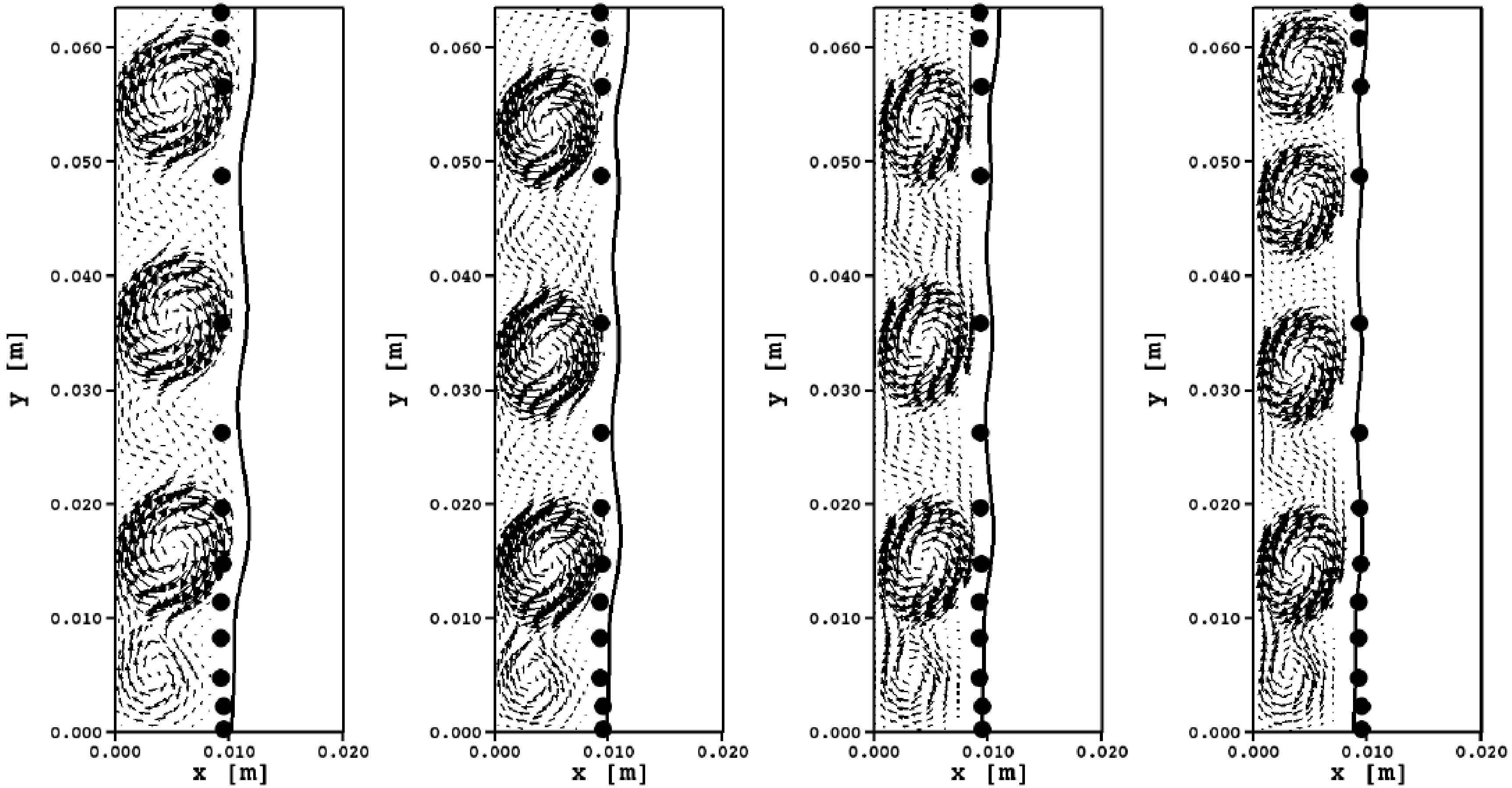
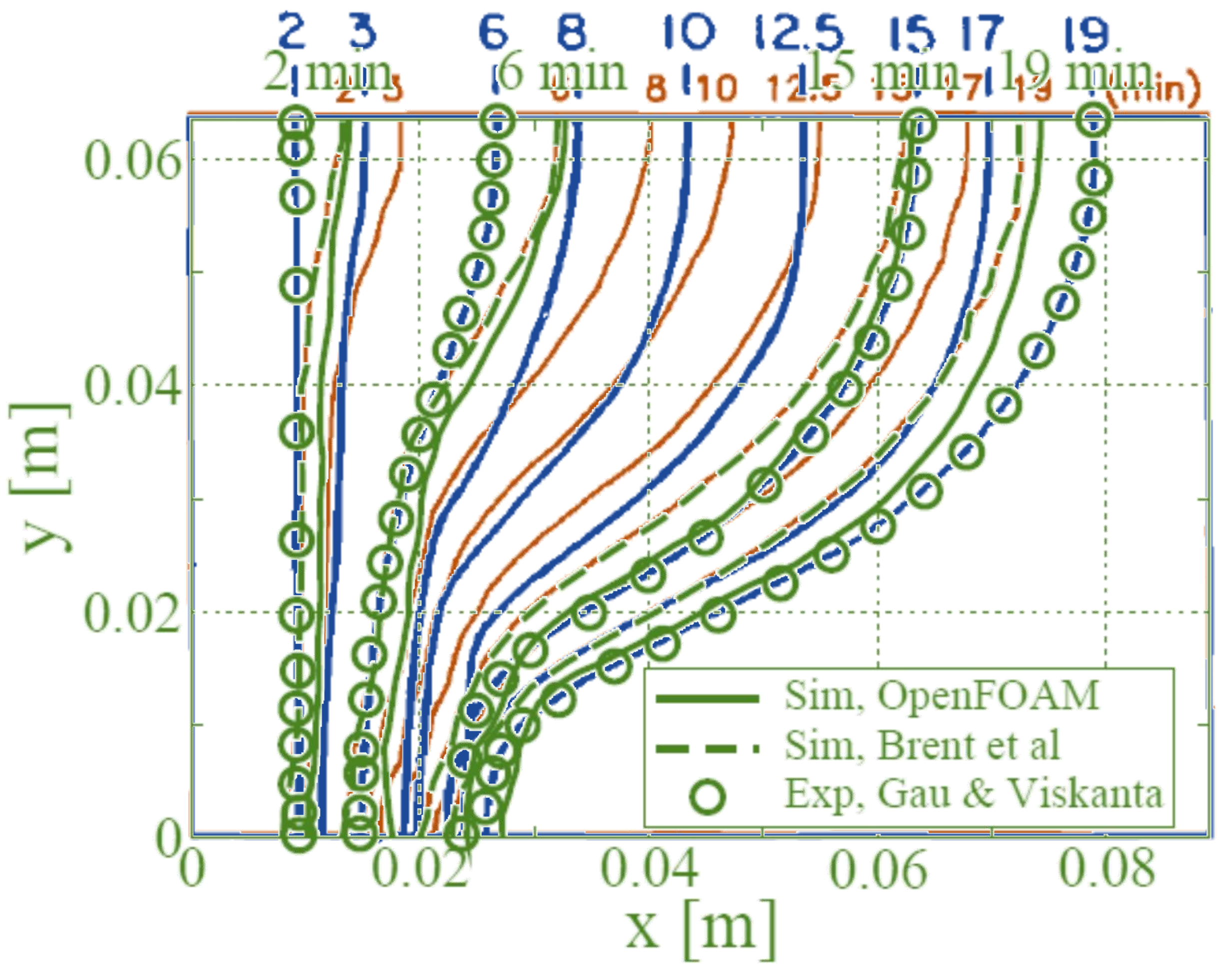
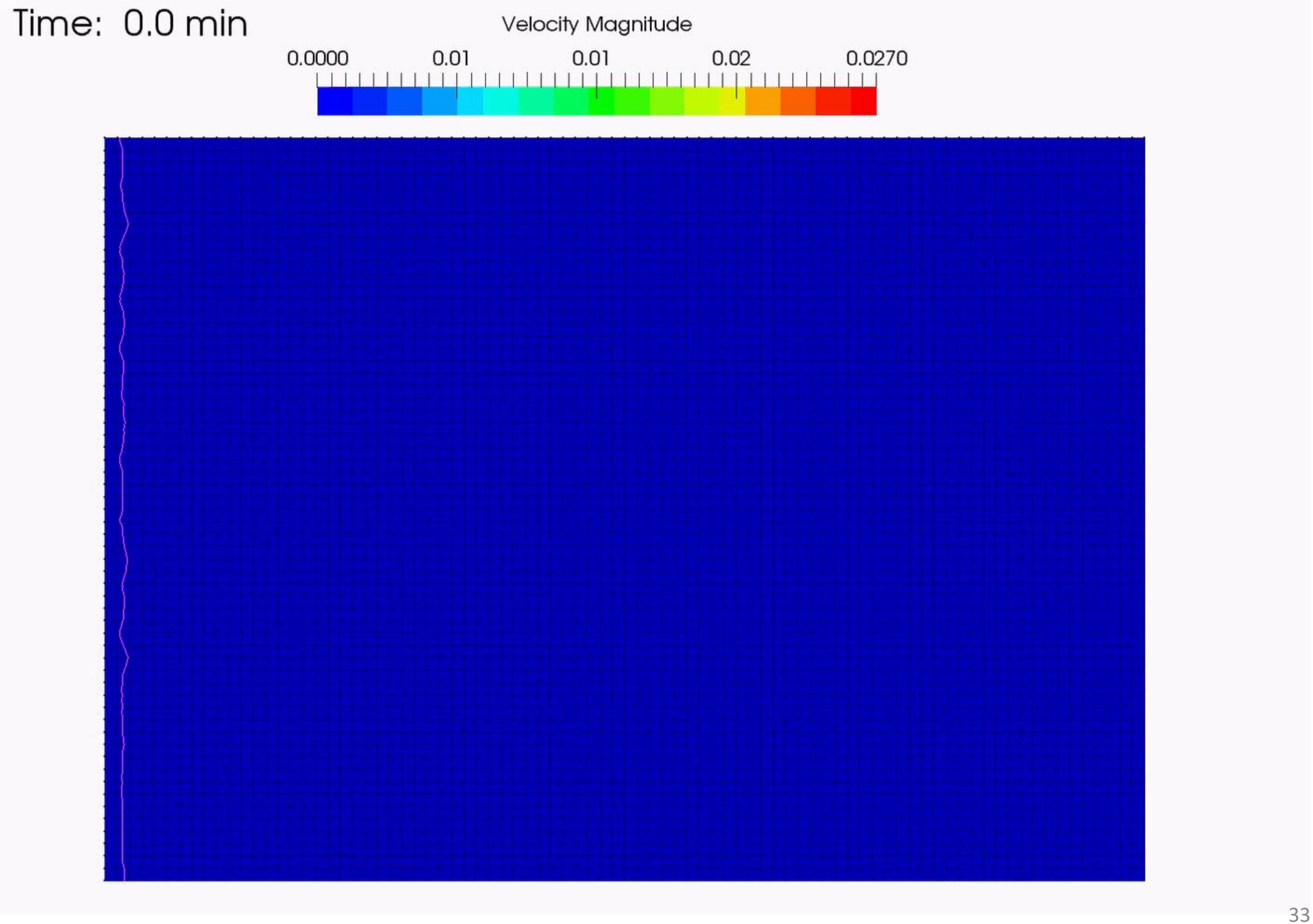


Figure 3.3. Simulated melt velocity field and melting front (solid line), and experimental melting front (circles, Gau and Viskanta (1986)) at t = 2 min, from left to right: mesh 280 × 200, 560 × 400, 840 × 600 and 1120 × 800, respectively.

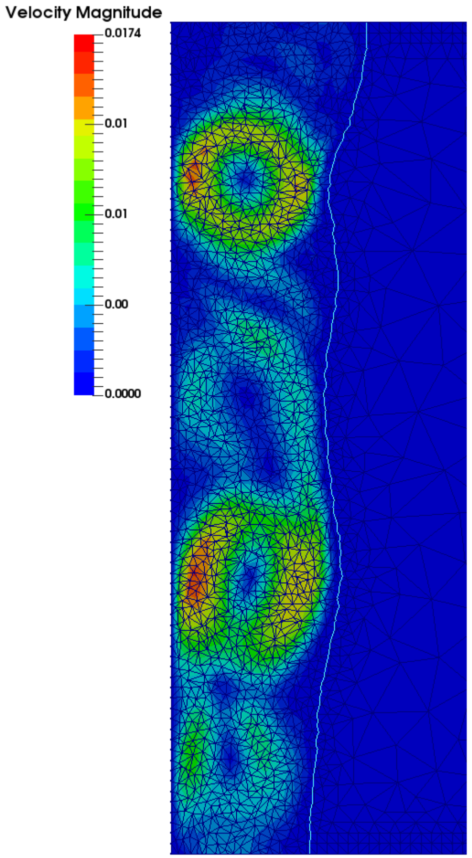
Literature 3: Saldi's PhD thesis (2012)



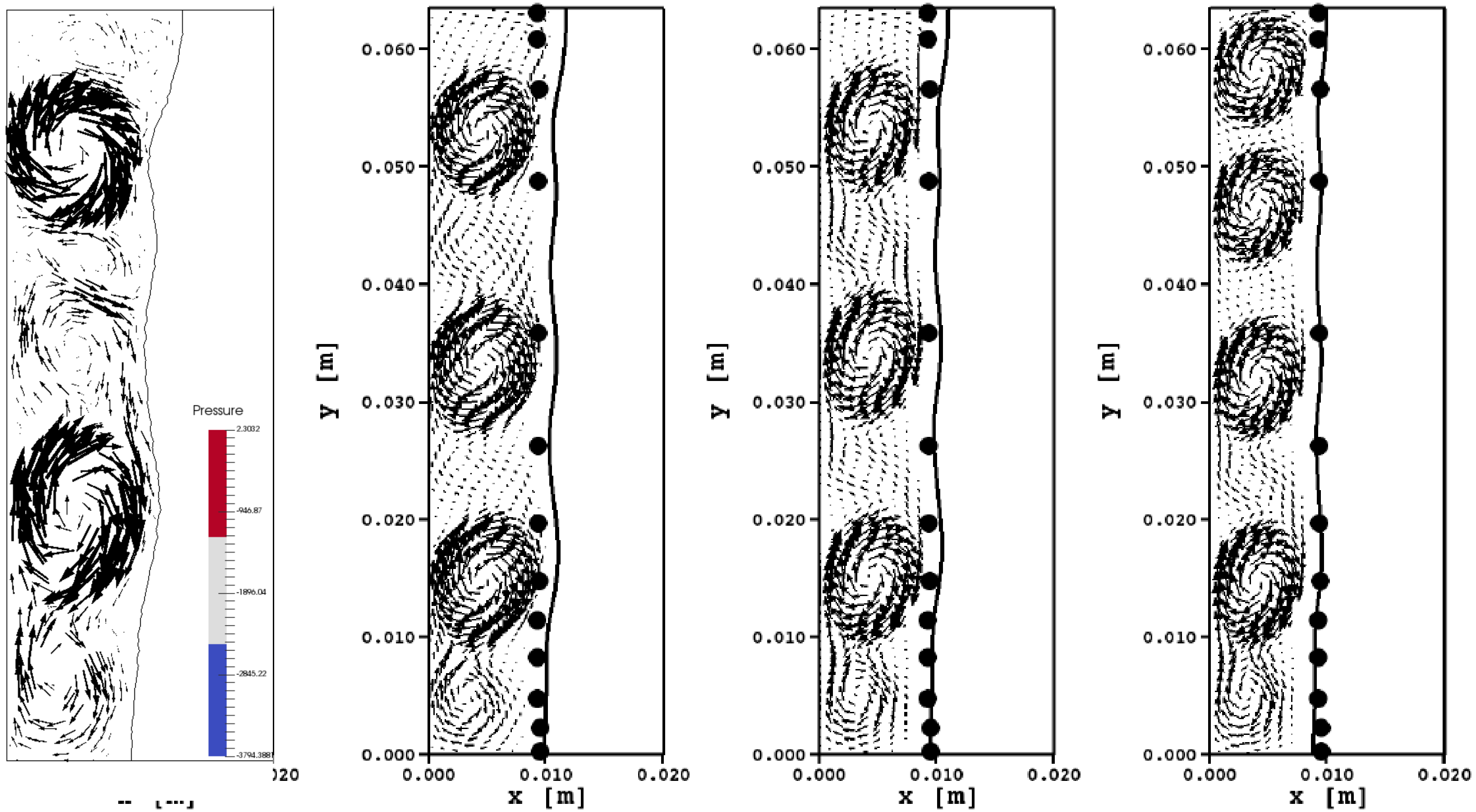
Brent et al. 1988 | Gau & Viskanta 1986 (exp.) | Saldi 2012


Time: 0.0 min
Velocity Magnitude
0.0000
0.01
0.01
0.02
0.0270

Velocity fields



- 80x112 mesh
- refinement
- free slip
- $\Delta T = 0.1\mathrm{K}$



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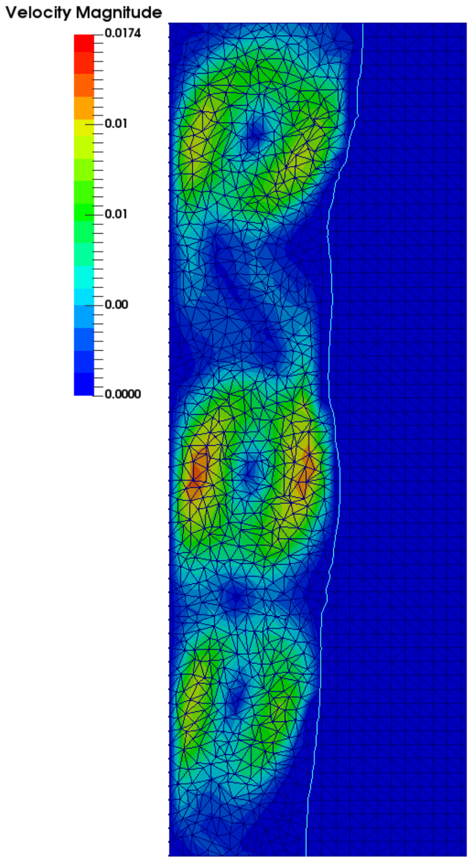
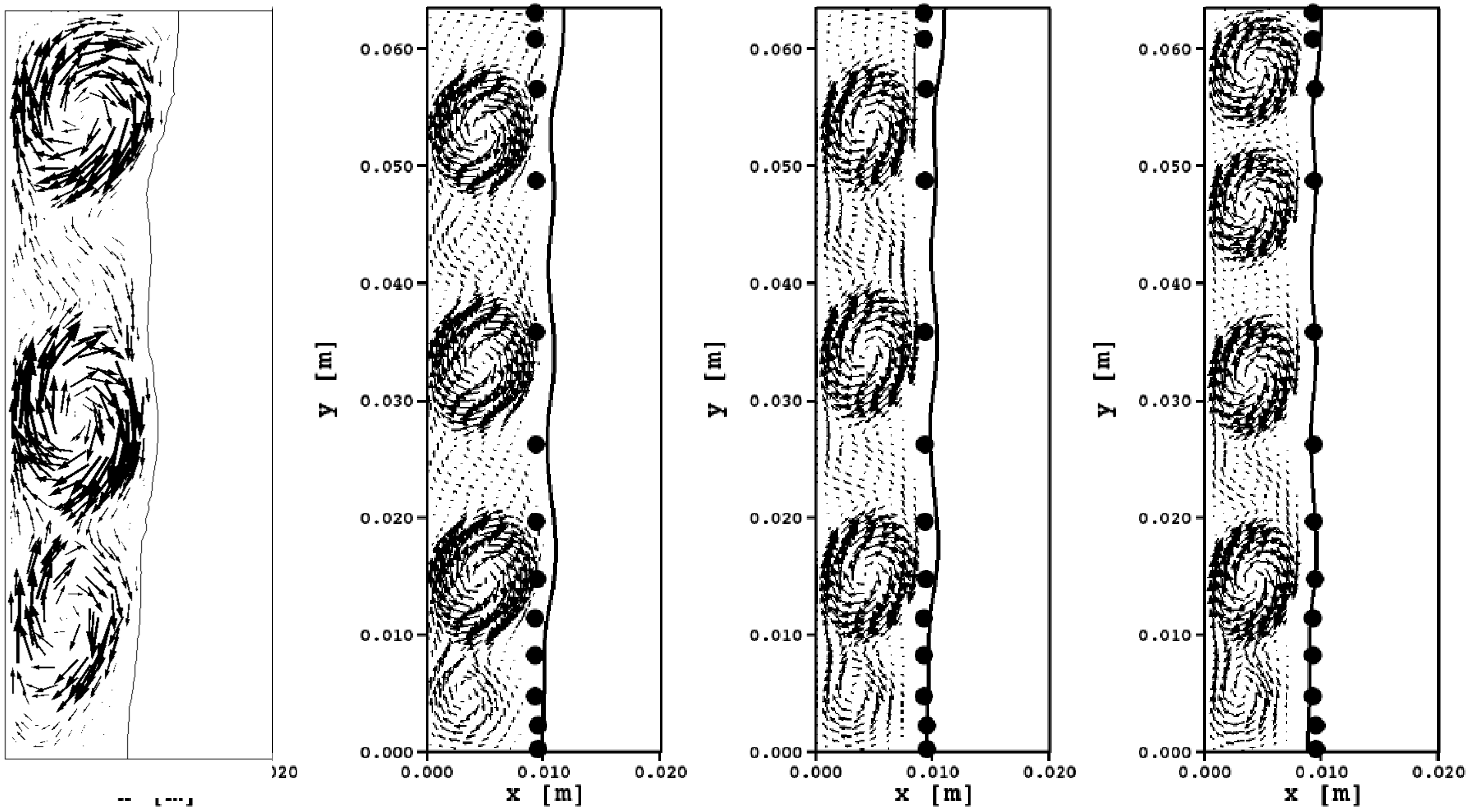
Velocity fields



- 60x84 mesh
- no refinement
- free slip
- $\Delta T = 0.1\text{K}$



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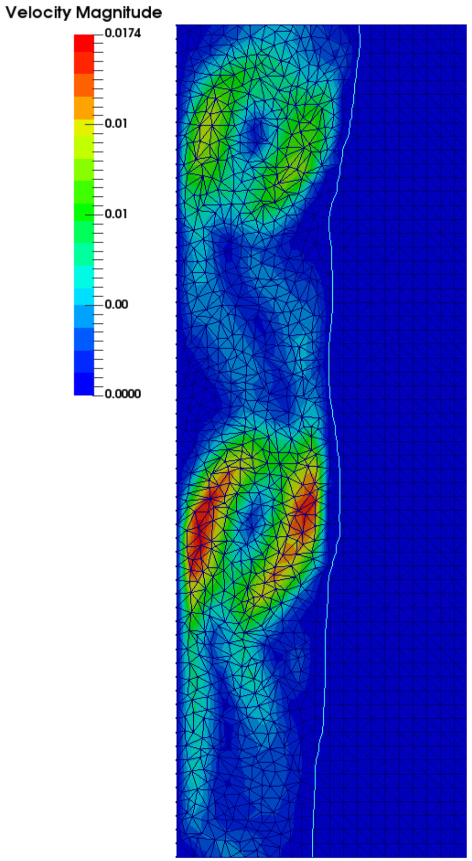
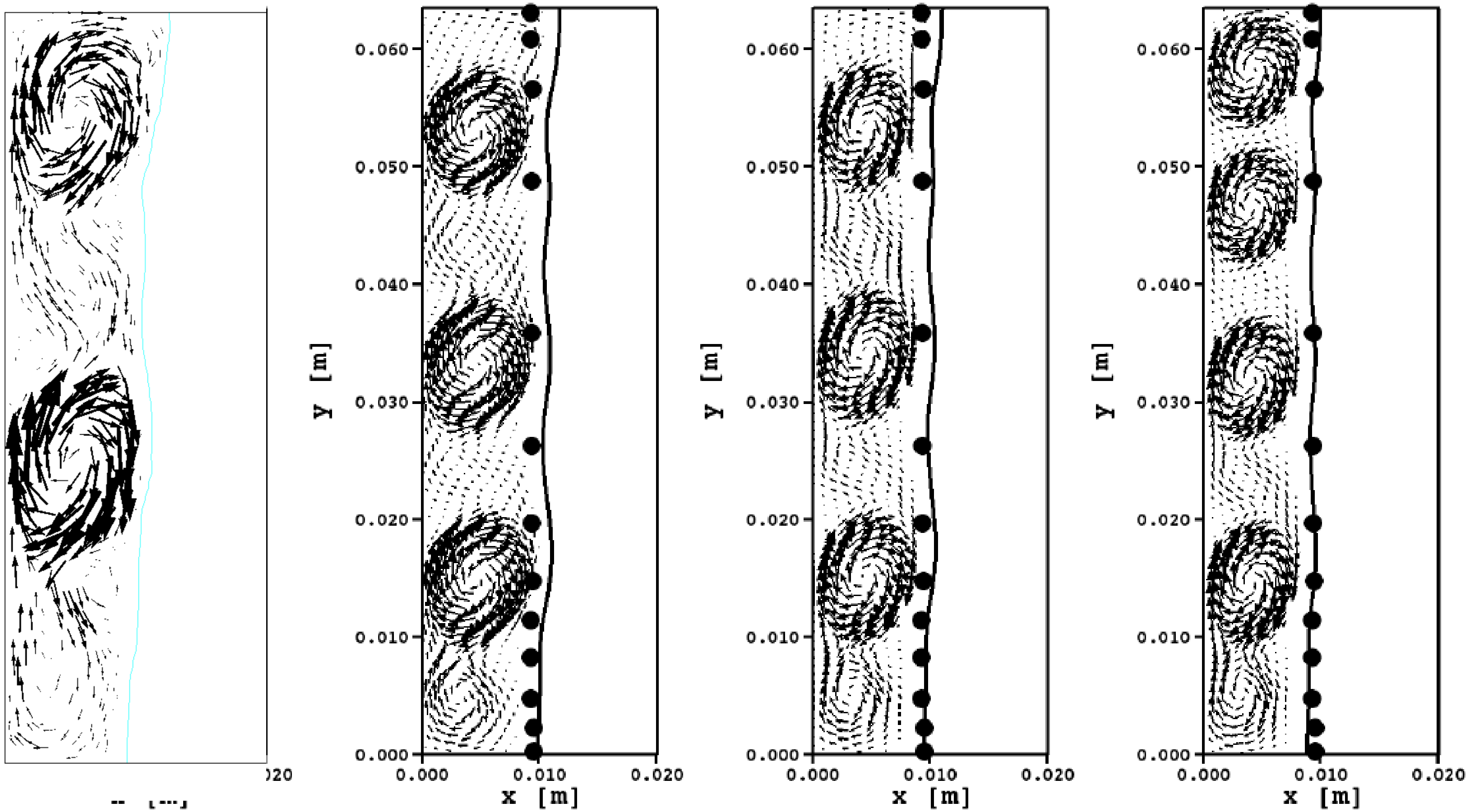
Velocity fields



- 60x84 mesh
- no refinement
- free slip
- $\Delta T = 0.2\text{K}$



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